Origami Tessellations as Variable Radiative Heat Transfer Devices

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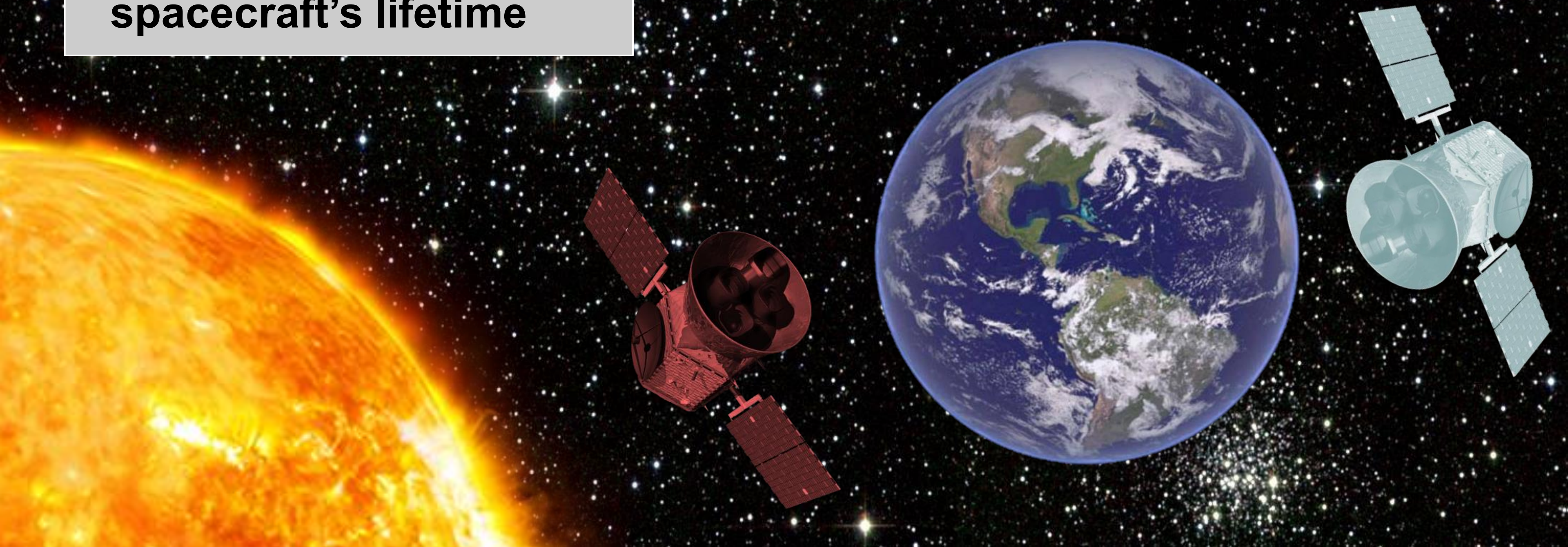
Variable Radiative Surfaces - Application

- Spacecraft experience varying thermal environments
- Radiators are sized to reject the maximum heat load, resulting in non-ideal radiator heat loss for a portion of the spacecraft's lifetime



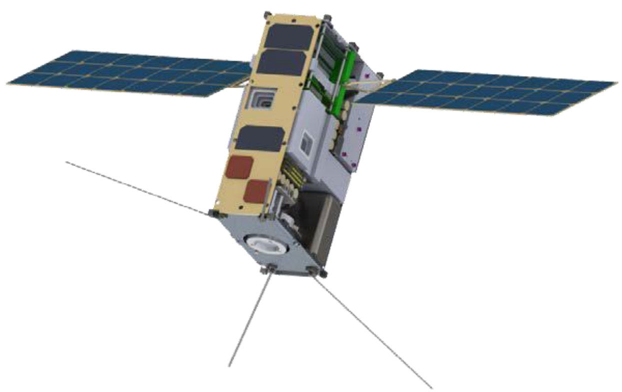
Variable Radiative Surfaces - Application

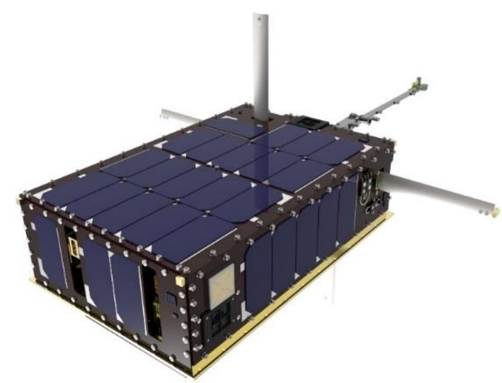
- A radiator capable of varying its thermal radiative properties would reject the ideal amount of heat to the environment at all times

<u>High Emissivity</u>
Reject as much heat as possible

Variable Radiative Surfaces - Application

- Variable Emissivity Devices would save weight and power
  - 5-7% of spacecraft power is heater related[1]
  - 2-10% of spacecraft dry weight is thermal control[1]
  - Expected power savings from variable emissivity: 90 - 75%[1]
- Variable Emissivity Devices would be especially useful for smaller spacecraft, such as CubeSats
  - Smaller thermal mass means larger temperature swings
  - Less power available for heaters
  - Higher watt density due to compact electronics





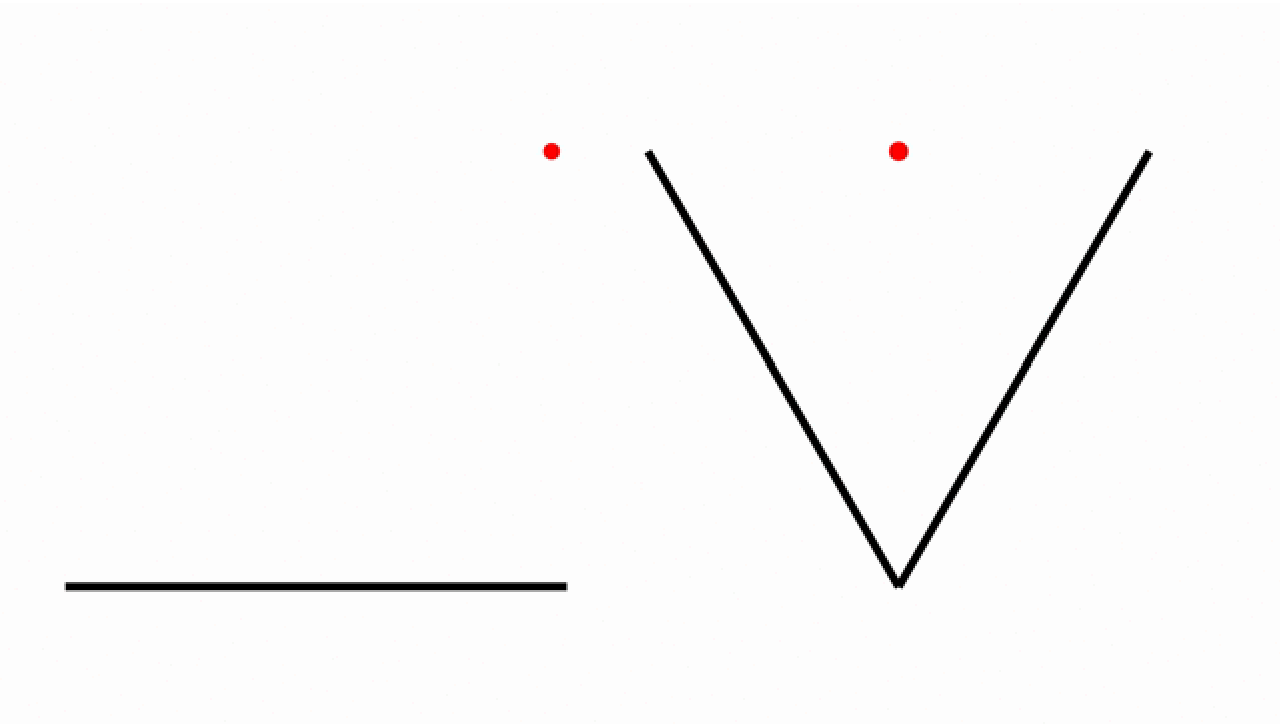
How do we modify radiative heat transfer in real time?

] – Gilmore, David G. "Spacecraft Thermal Control Handbook: Technology Projections." 2002. 2nd Edition.

The Cavity Effect - Definition

- Reflections inside a cavity result in increased apparent absorptivity
- Apparent properties depend on cavity geometry

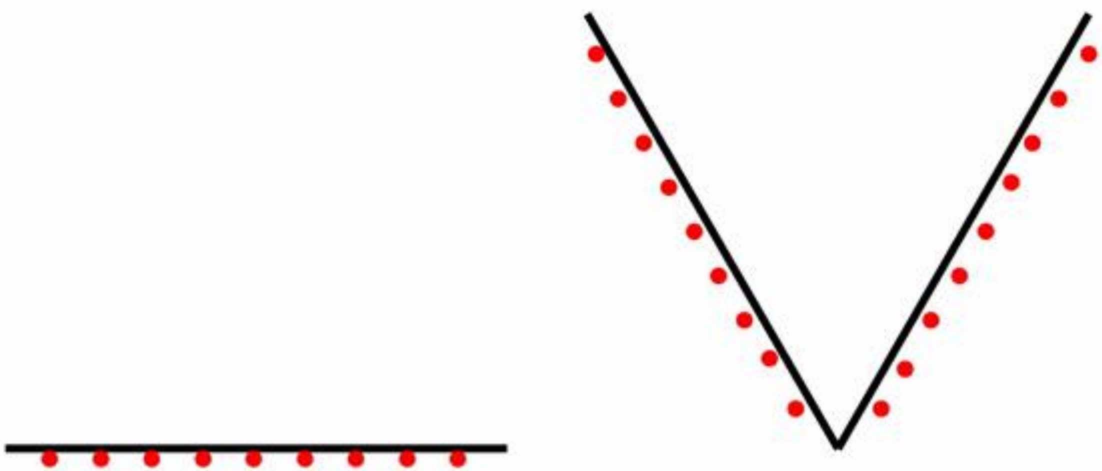
$$\alpha_a = \frac{G_{absorbed}}{G_{incident}}$$



The Cavity Effect - Definition

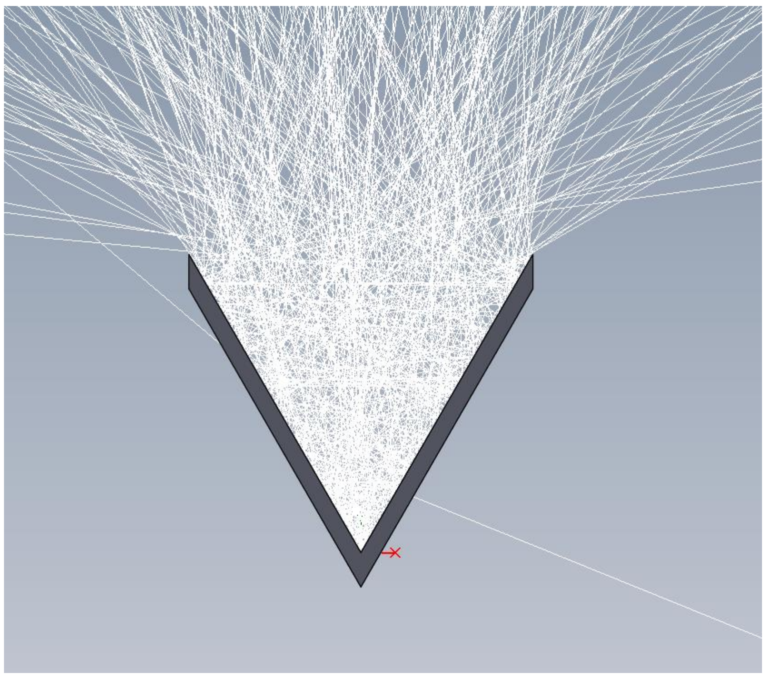
- A cavity concentrates emission from all internal surfaces to the cavity opening, increasing the apparent emission from the opening

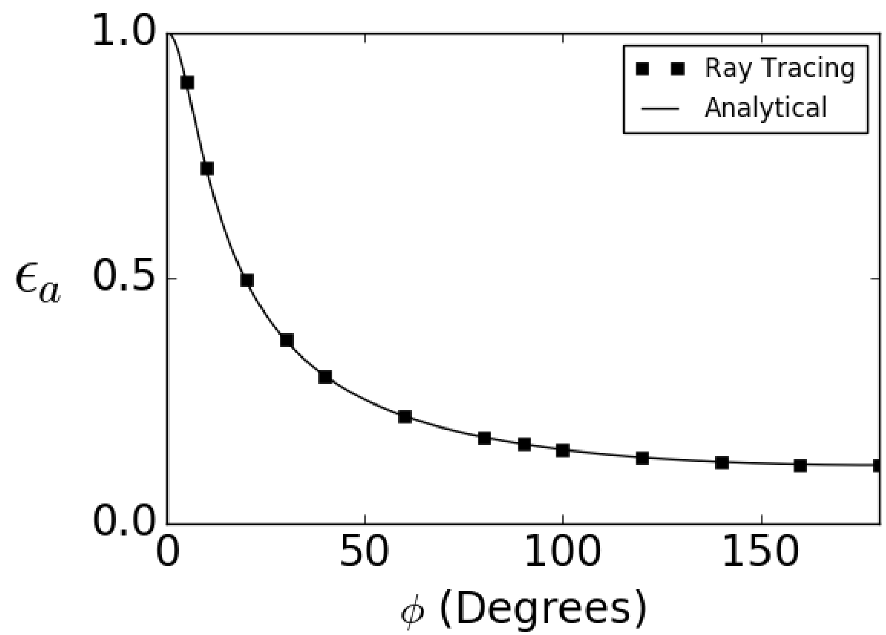
$$\varepsilon_a = \frac{E_{cavity}}{E_{blackbody}}$$



The Cavity Effect - Benefits

- Different surfaces give different performance
- Deep cavities result in near black behavior
- Cavity emission is ***highly directional***, allowing for control of directional radiative heat transfer

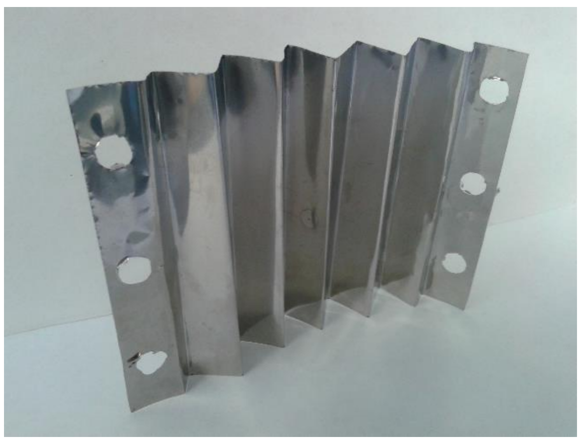


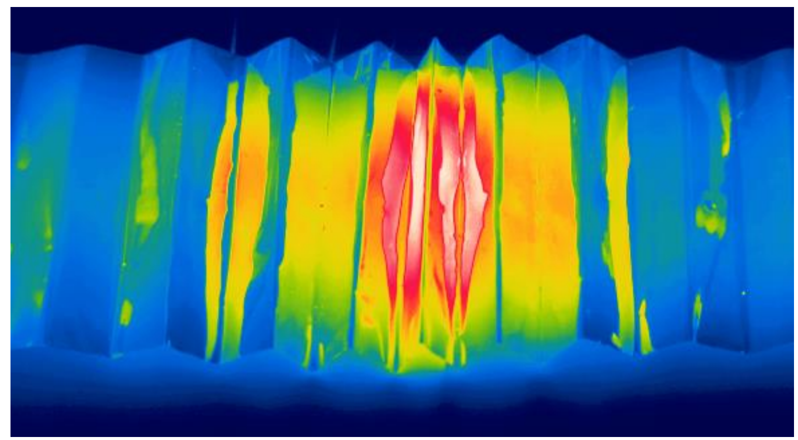


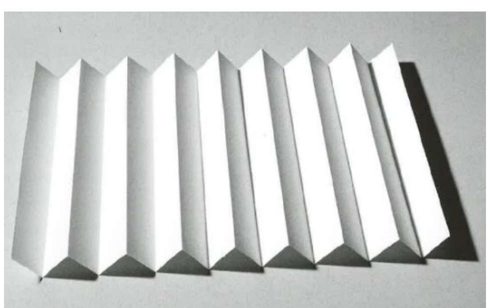
How do we modify radiative heat transfer in real time?

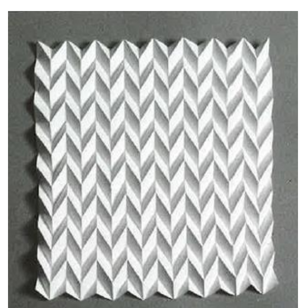
The Cavity Effect – Origami

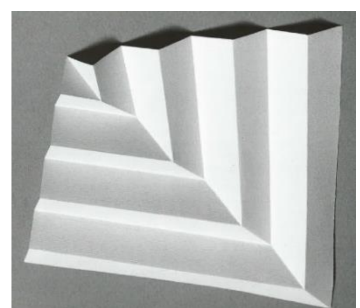
- Origami tessellations control cavity aspect ratio through actuation
- **But what are the apparent radiative properties?**
- **How would these be applied to a real scenario?**

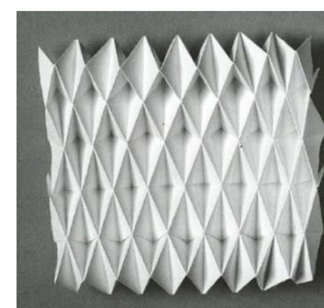












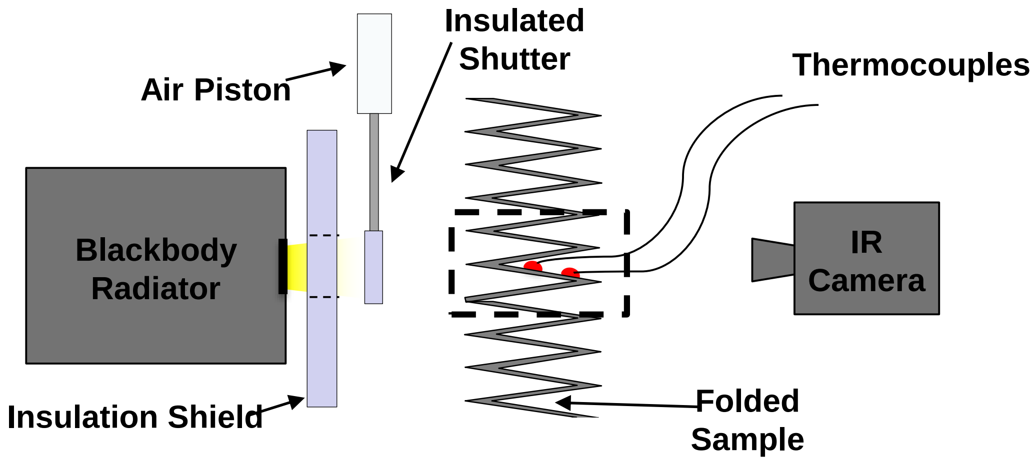
Research Objectives

1. Demonstrate a change in apparent properties with geometry
2. Characterize the apparent emissivity and apparent absorptivity of four tessellations
3. Validate the ability of a dynamically-actuated tessellation to control temperature when exposed to a varying thermal environment.
4. Develop initial radiator prototypes

Demonstrate a change in apparent properties with geometry

OBJECTIVE 1

Objective 1 - Approach

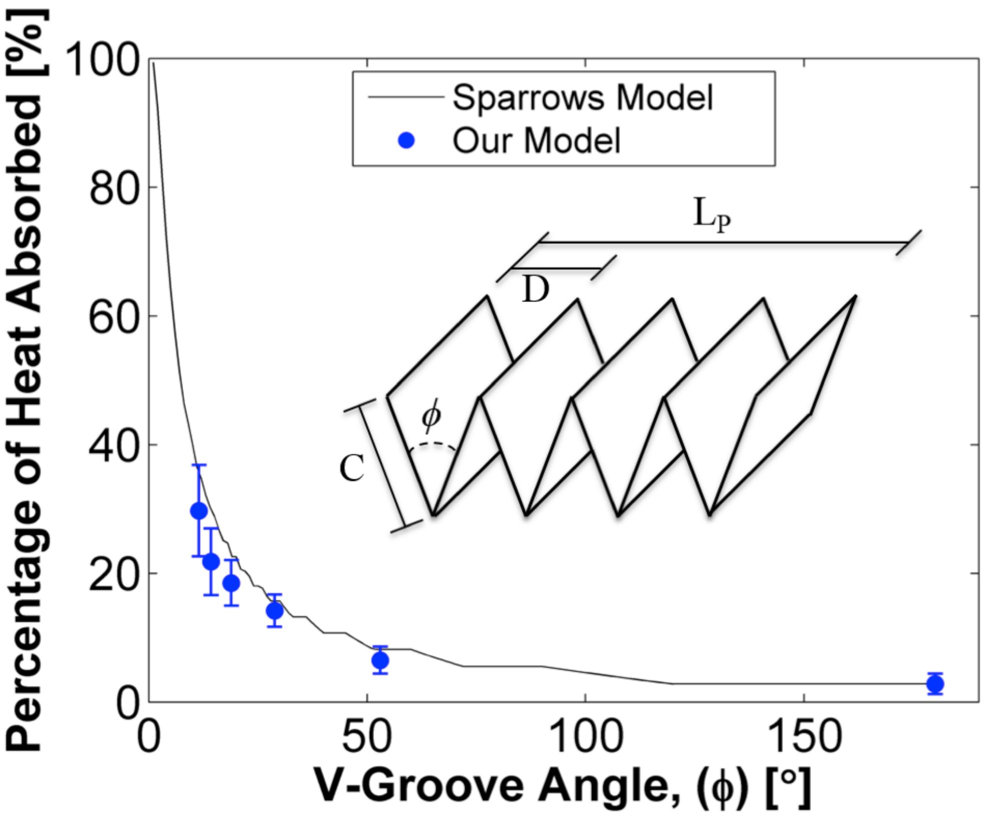


- A piece of aluminum shim stock folded into an accordion tessellation was repeatedly heated and cooled in ambient conditions
- The cooling temperature curve gave information about heat losses
- The heating energy balance gave an expression for absorptivity

$$\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]\theta = \sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P} \Rightarrow \boxed{\alpha_a = \frac{\frac{U_{\max}}{G_B}\left(\theta - \theta_0\right)}{1 - e^{\frac{-U_{\max} t}{\rho w C_P}\sin\left(\frac{\phi}{2}\right)}}}$$

Objective 1 – Results

- Inverse model results[2] were compared to Sparrow's work[3]
- **Apparent absorptivity increase is experimentally verified**



Sparrow's Equations

$$\alpha_a = 1-(1-\alpha X')(1-\alpha)^{n-1}$$

where:

$$X' = \frac{\sin\left[\left(n-\frac{1}{2}\right)\phi\right]}{\sin\left(\frac{\phi}{2}\right)}$$

$$n = \left\lfloor \frac{180}{\phi} + \frac{1}{2} \right\rfloor$$

[2] – Mulford et al. "Dynamic control of radiative surface properties with origami-inspired design" 2016. JHT.
[3] – Sparrow and Lin. "Absorption of thermal radiation in a V-groove Cavity." 1962. IJHMT 5.

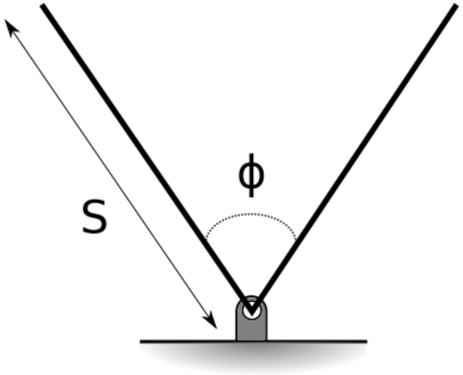
Characterize the apparent radiative properties of four origami tessellations

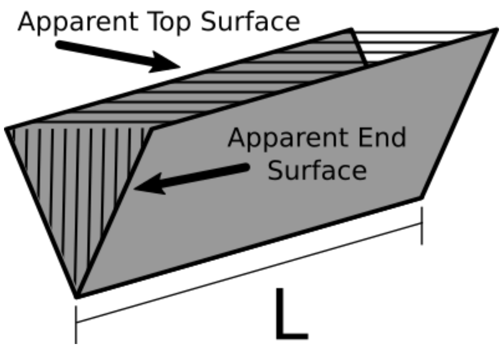
OBJECTIVE 2

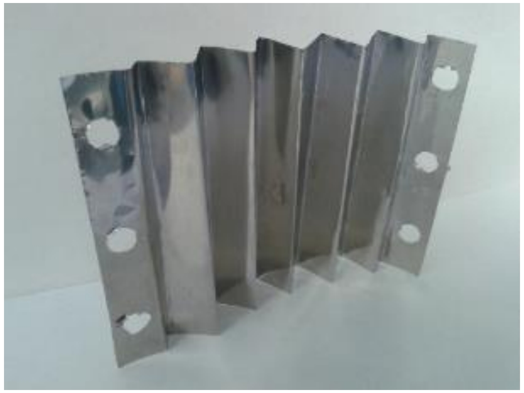
Objective 2 - Definition

- **Models must be developed to characterize the apparent radiative properties of origami tessellations**

Accordion



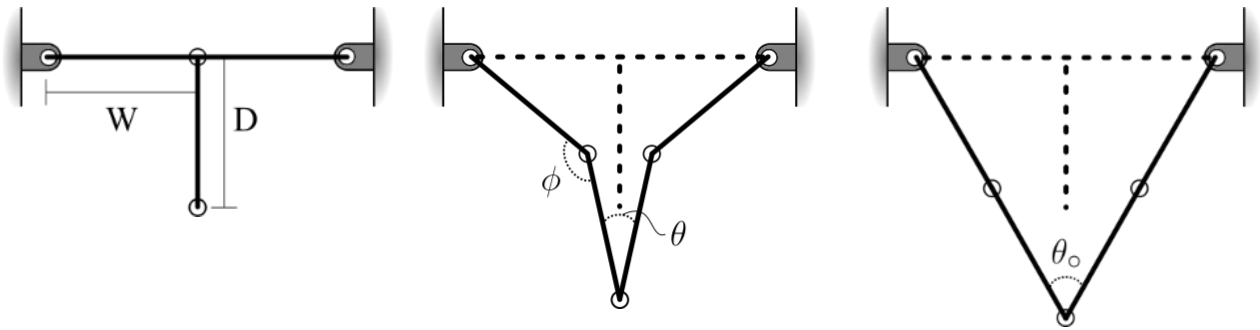




- Benefits
  - Easy to fold, similar to infinite V-groove.
  - Collapses and expands, allowing for storage
  - Easy to model and test

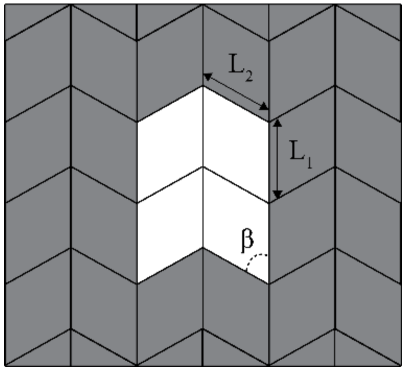
Objective 2 - Definition

Hinged V-groove

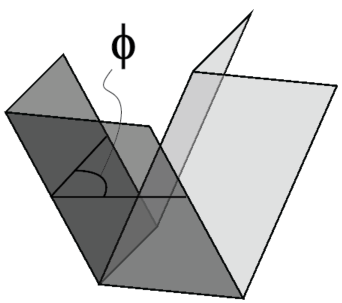


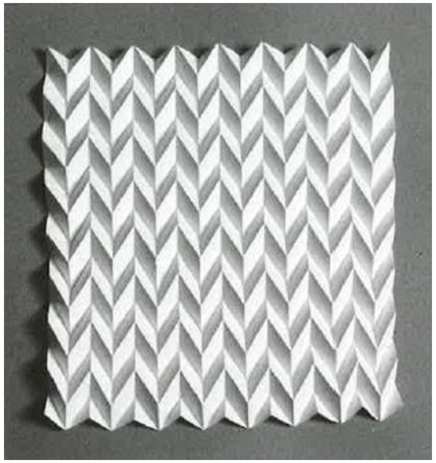
- Benefits
  - Maintains a constant projected surface area while actuating
  - Two geometry parameters for control

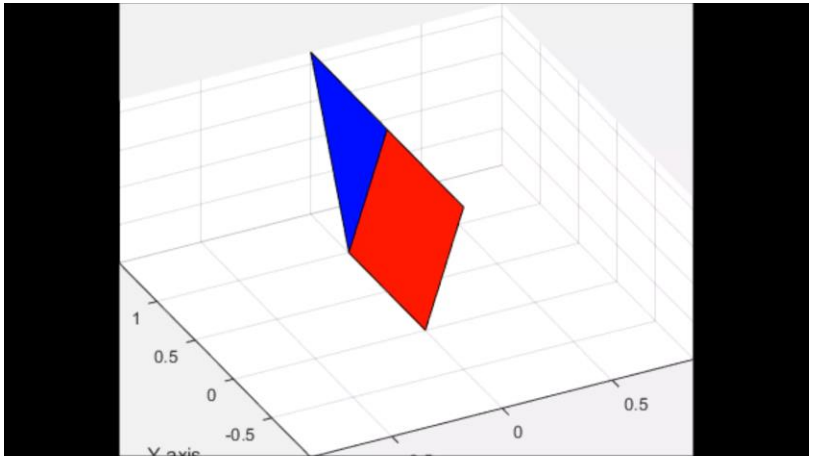
Objective 2 - Definition



Miura-Ori



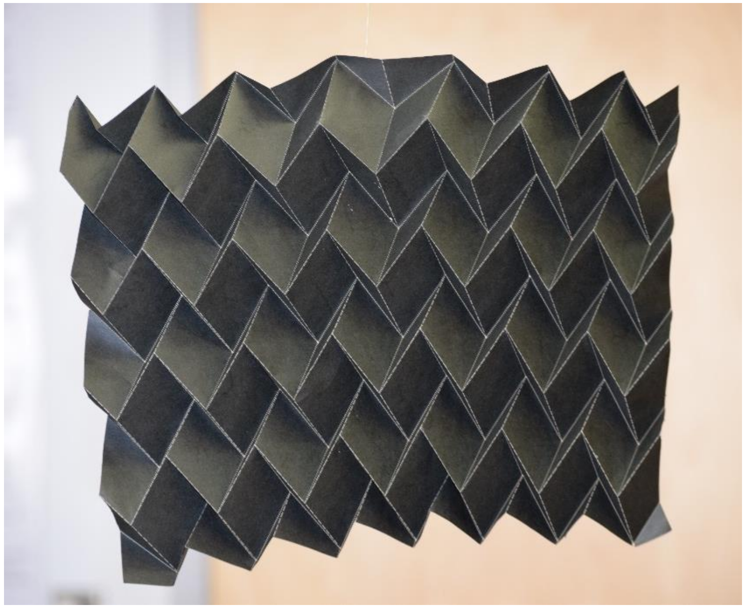


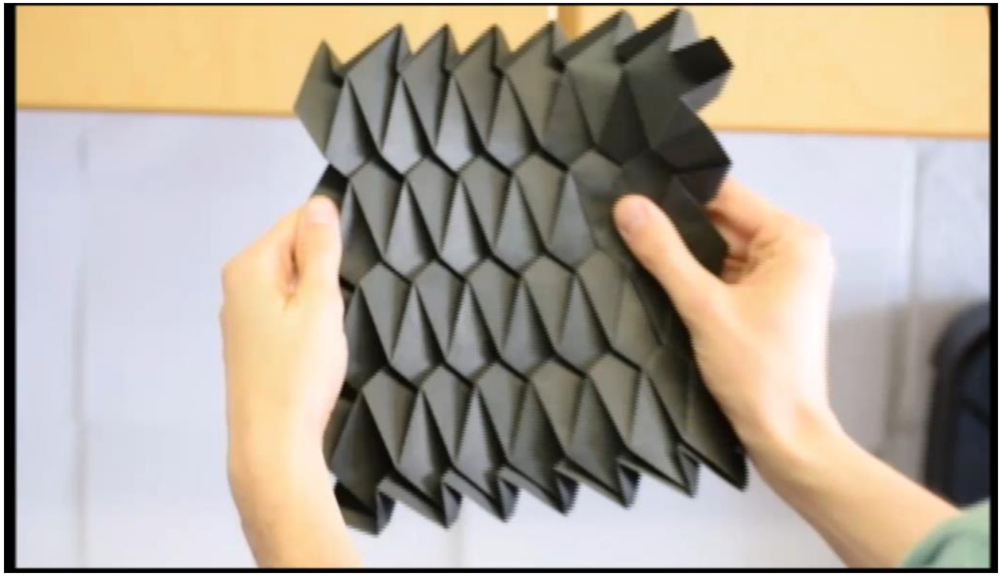


- Benefits
  - Linear actuation results in 3D movement
  - Three geometry parameters for control
  - Collapses and expands, allowing for storage

Objective 2 - Definition

Barreto's Mars



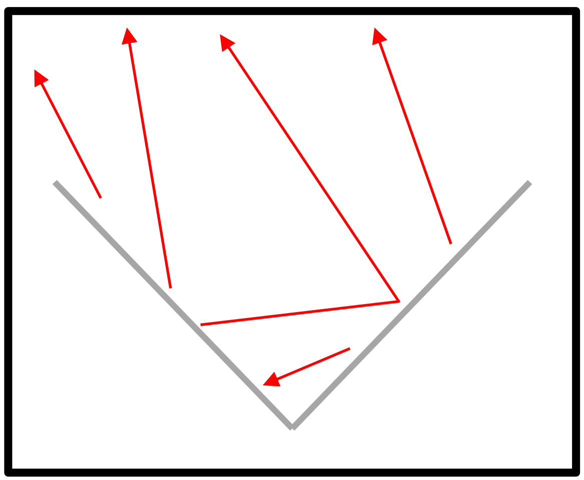


- Benefits
  - Cavities collapse to one side, giving a large absorptivity in one direction and great reflectivity in the other direction
  - Collapses to a finite area
  - Would give interesting directional behavior

Objective 2 – Approach: Ray Tracing

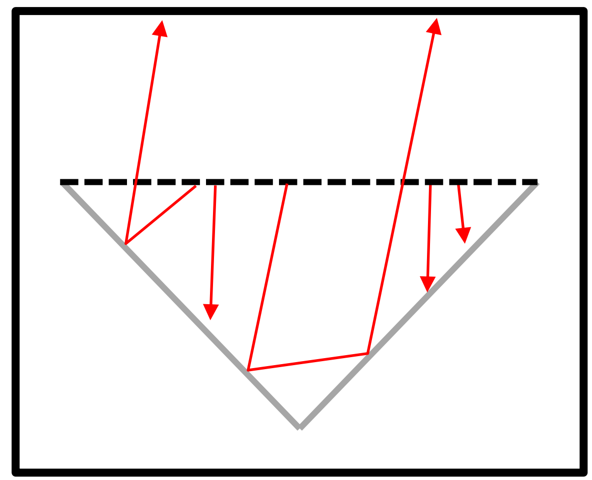
- Rays are emitted from a surface or irradiated onto a surface.
- This approximates an isothermal surface (for emission).
- The number of rays emitted (N_{emit}) and the number of rays absorbed by the cavity ($N_{absorbed}$) are counted.

Apparent Emissivity



$$\varepsilon_a = \varepsilon\left(\frac{A_{emit}}{A_{open}}\right)\left(\frac{N_{escape}}{N_{emit}}\right)$$

Apparent Absorptivity

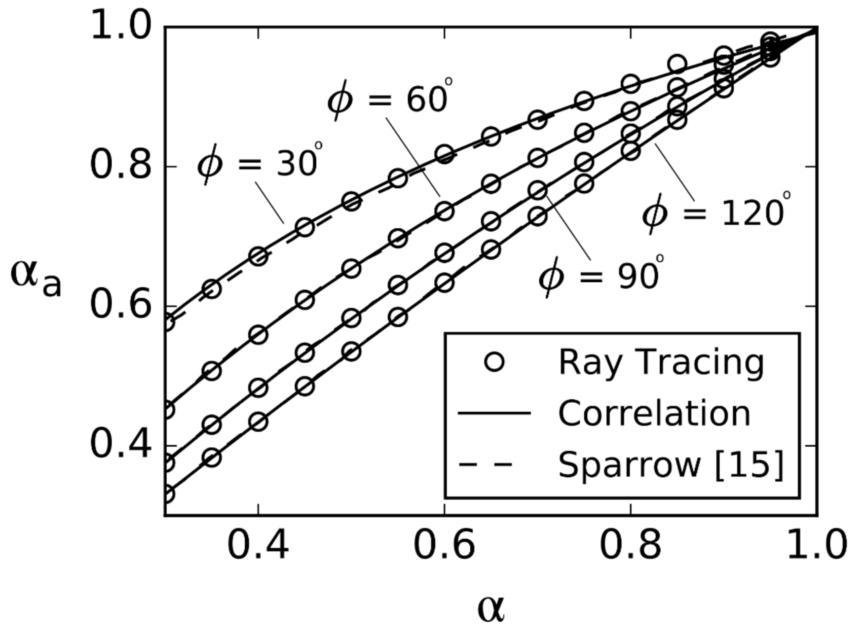


$$\alpha_a = \frac{N_{absorb}}{N_{emit}} = \varepsilon_a$$

diffuse emission
diffuse irradiation

Objective 2 – Results: Ray Tracing

Infinite V-groove – Diffuse Irradiation

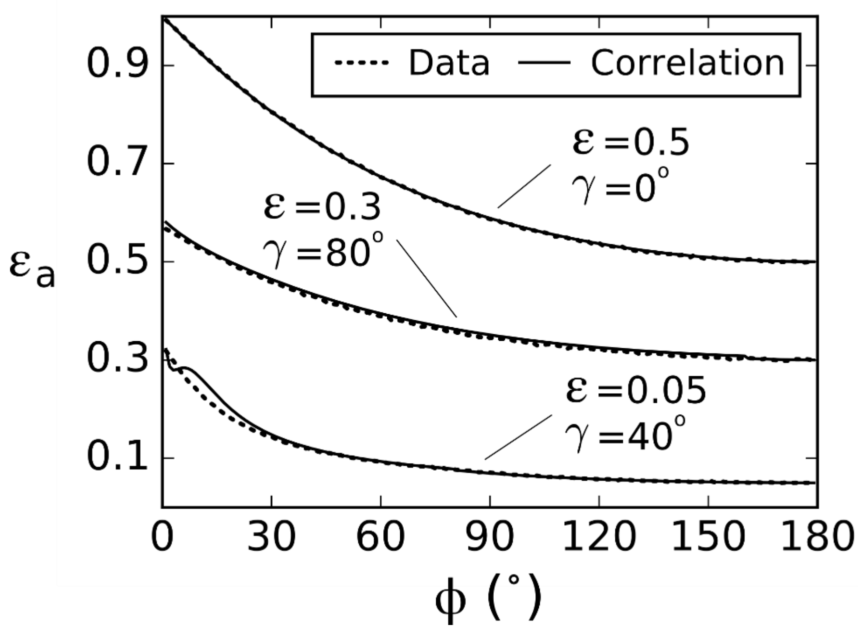


$$\varepsilon_a = \varepsilon\,\Lambda_1(\varepsilon,\phi)\sum_{n=0}^{\infty}(1-\varepsilon)^n\left[1-\sin\left(\frac{\phi}{2}\right)\right]^n = \alpha_a$$

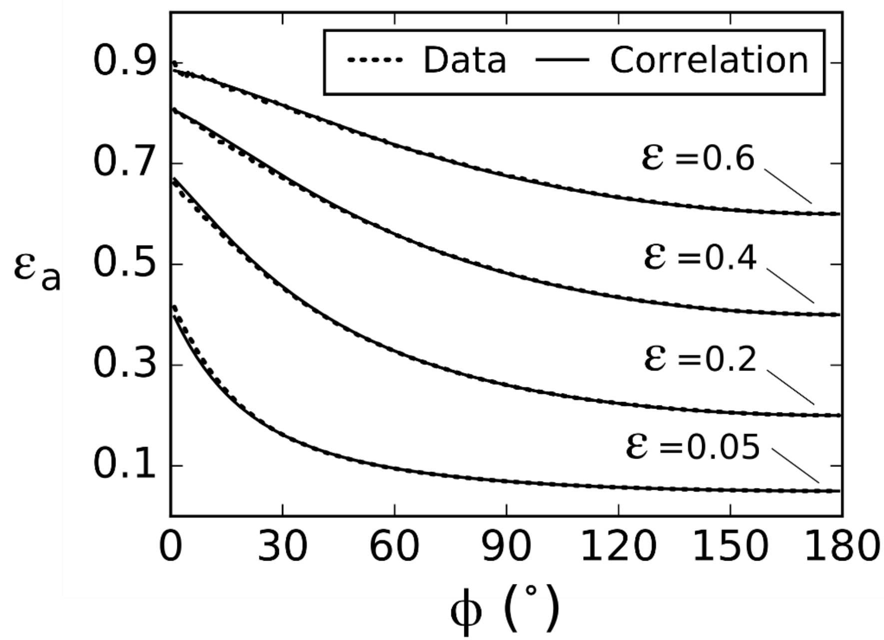
$$\Lambda_1(\varepsilon,\phi) = 1-\left(0.0169-0.1900\ln(\varepsilon)\right)\exp\left(-1.4892\varepsilon^{-0.4040}\phi\right)$$

Objective 2 – Results: Ray Tracing

Infinite V-groove



Collimated Irradiation – Steep Inclination

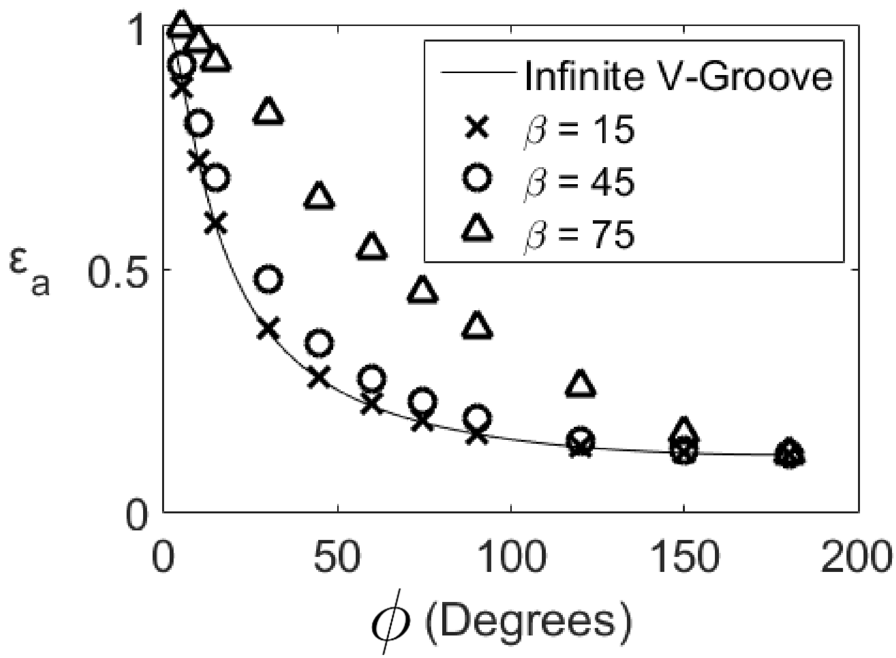


Diffuse Irradiation

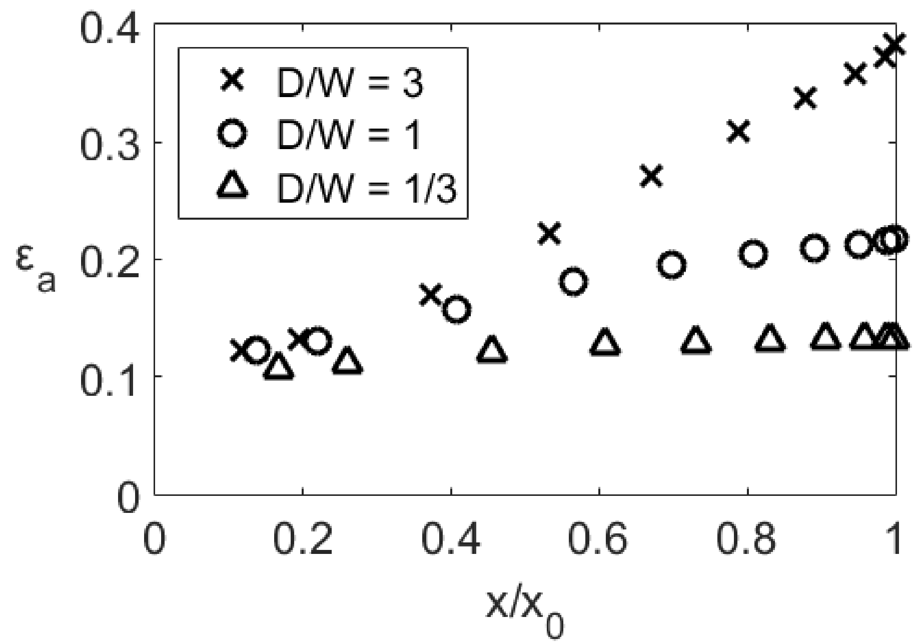
- Accordion fold results will be similar to infinite V-groove but will depend on the length of the panels as well.

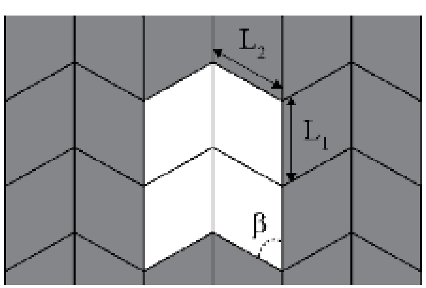
Objective 2 – Results: Ray Tracing

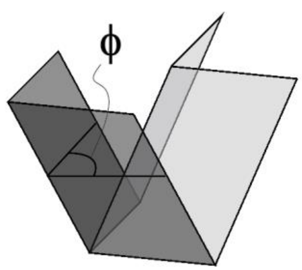
Miura-Ori

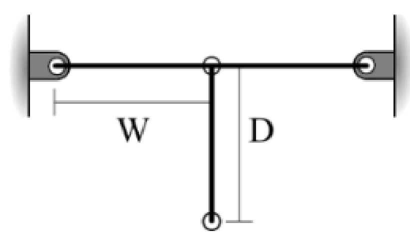


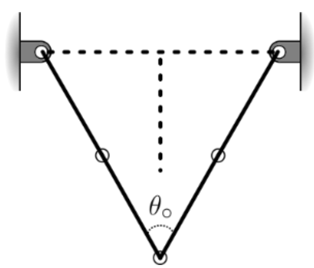
Modified V-groove









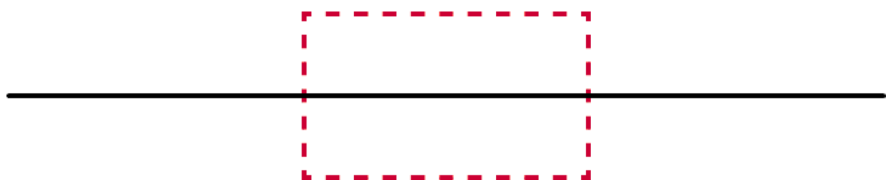


Validate the ability of a dynamically-actuated tessellation to control temperature when exposed to a varying thermal environment.

OBJECTIVE 3

Objective 3 - Definition

- This work will explore the use of origami tessellations as variable emissivity radiators for spacecraft applications
- To this end, two experiments will be conducted
  - Quantify the net rate of radiative heat exchange with the surroundings
  - Validate the ability of the surface to maintain a given thermal condition in a changing thermal environment

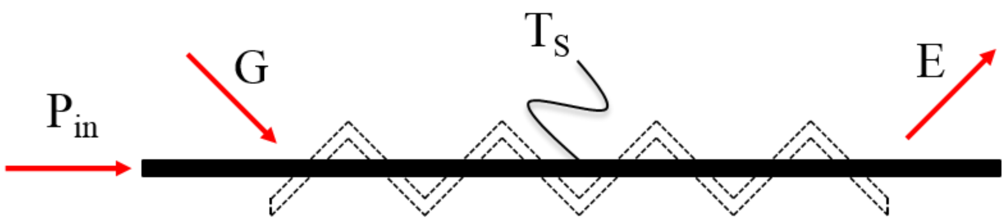


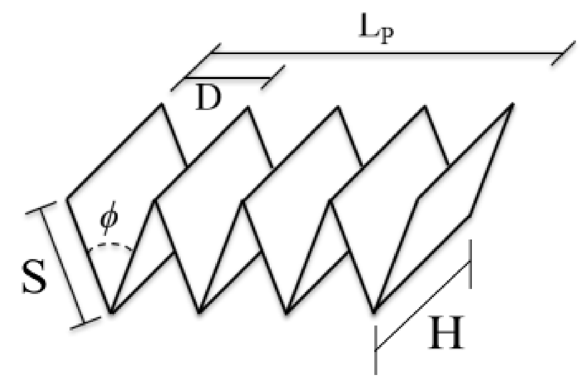
?

$$q_{net\_rad} = \varepsilon_a A_{projected} \sigma T^4$$

Objective 3 – Approach: Net Rad HT

- Consider a flat or folded tessellation subjected to uniform heat generation inside of a vacuum environment.





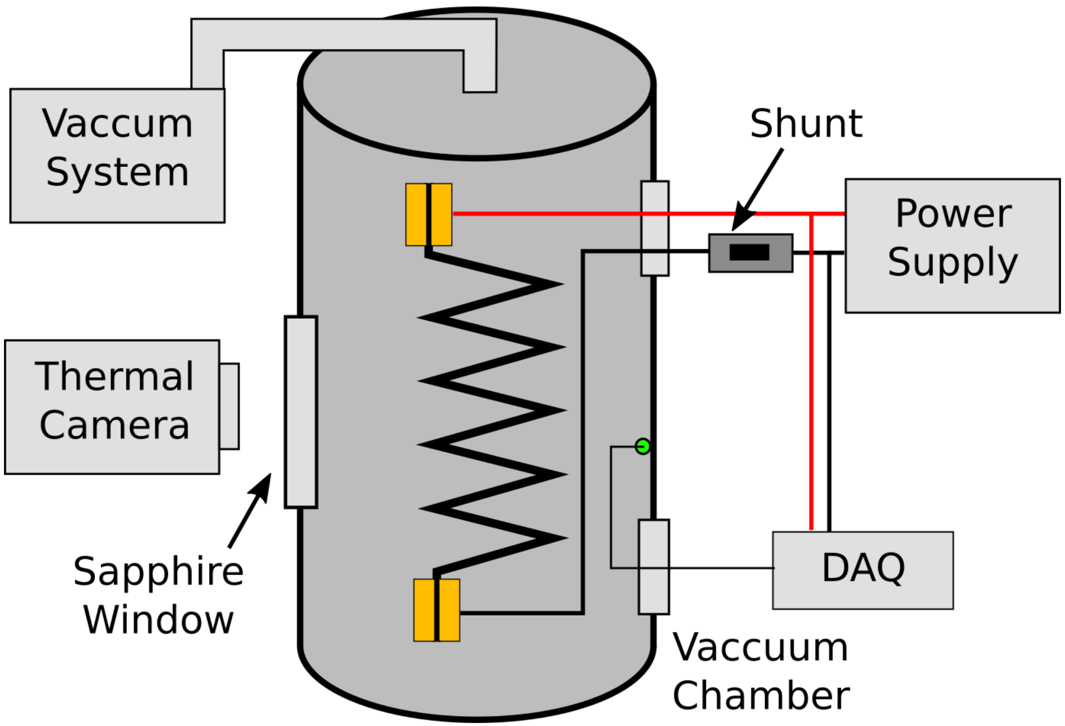
Diffuse or Collimated Irradiation / Diffuse or Specular Reflection

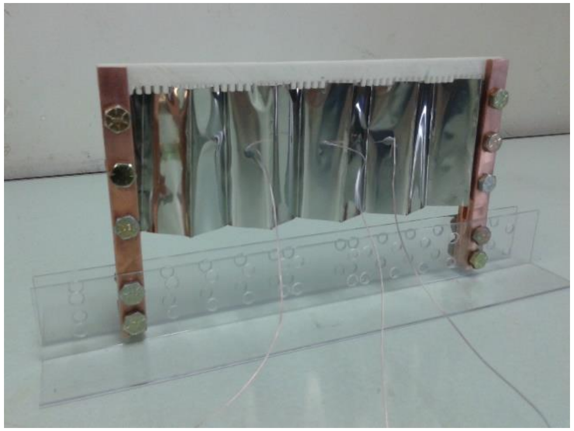
$$q'_{net,rad} = \left[N_{panels} - 1\right]\left[2W_P \sin\left(\frac{\phi}{2}\right)\right]\sigma\varepsilon_a(\phi)\left(T_S^4 - T_{surr}^4\right)$$

$$-\alpha_a \cos(\gamma)\left[\frac{N_{panels}}{2}\right]2W_P \sin\left(\frac{\phi}{2}\right)G$$

Objective 3 – Approach: Net Rad HT

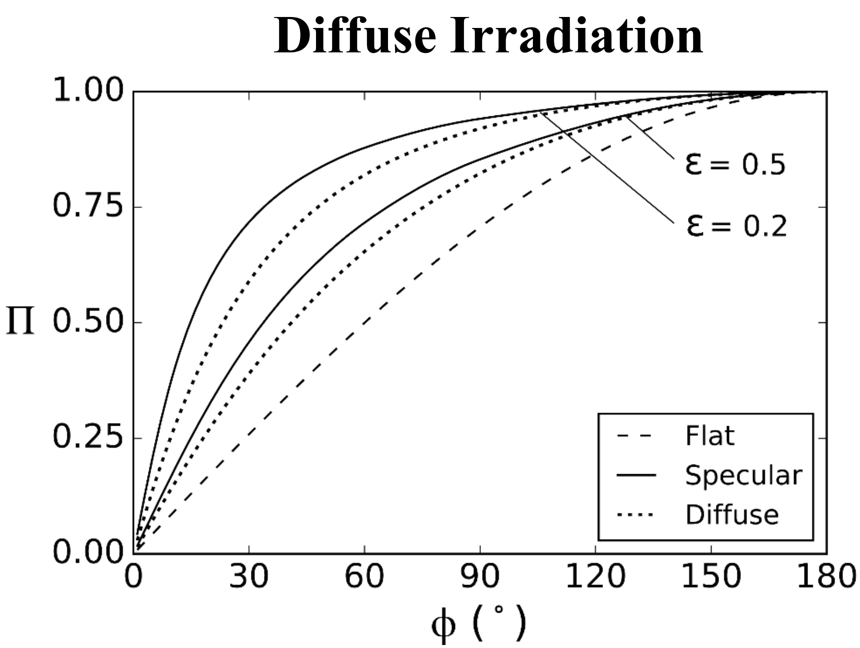
- Experimental methods are used to validate the model.
- A sample is heated internally in a vacuum chamber evacuated to below 10^{-5} Torr. A thermal camera records apparent temperature data through the sapphire window.

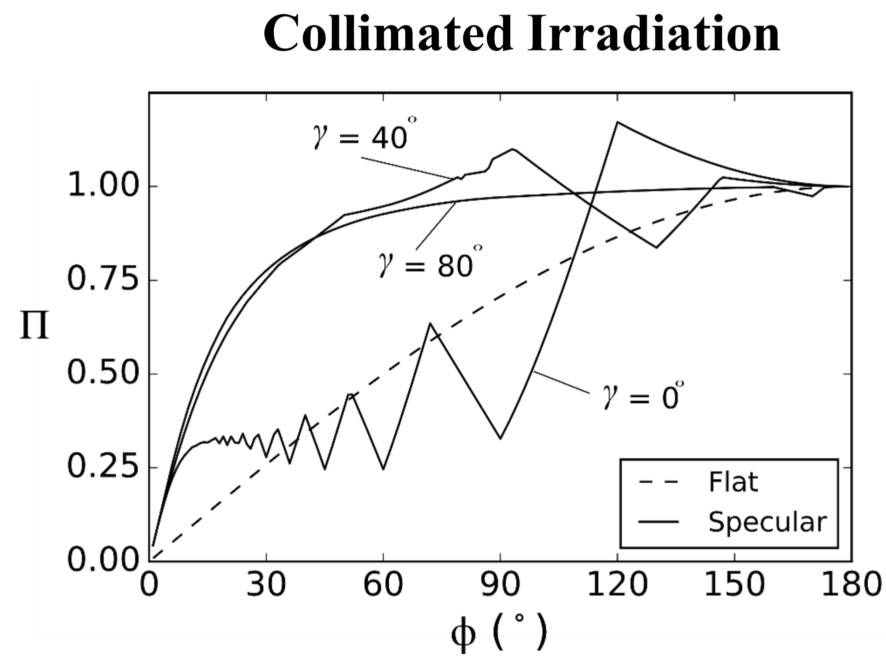




Objective 3 – Results: Net Rad HT

- Diffuse reflection: net radiative heat transfer decreases as the tessellation collapses despite increasing radiative properties
- Specular reflection and collimated irradiation: large changes in radiative properties over small periods are possible

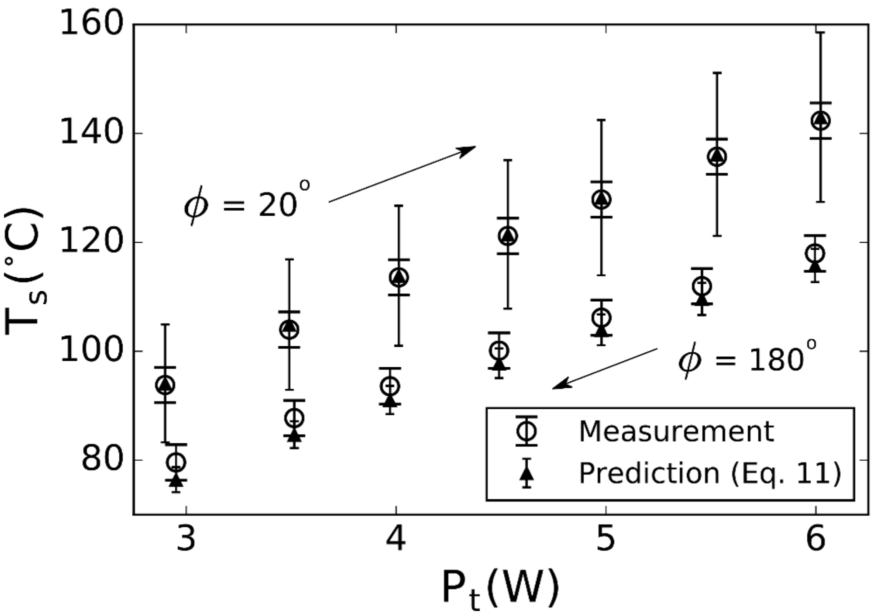


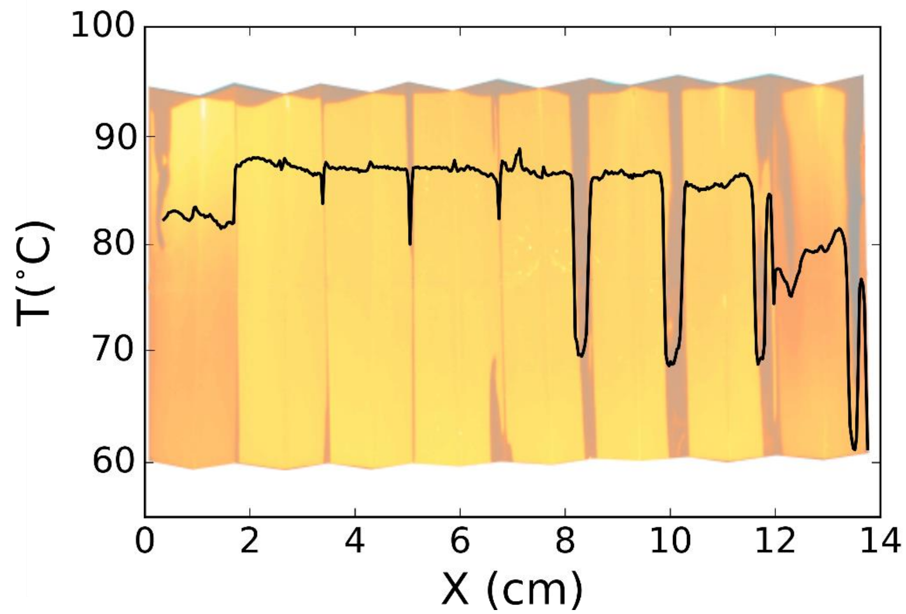


$$\Pi = \frac{q_\phi}{q_{\phi=180^o}}$$

Objective 3 – Results: Net Rad HT

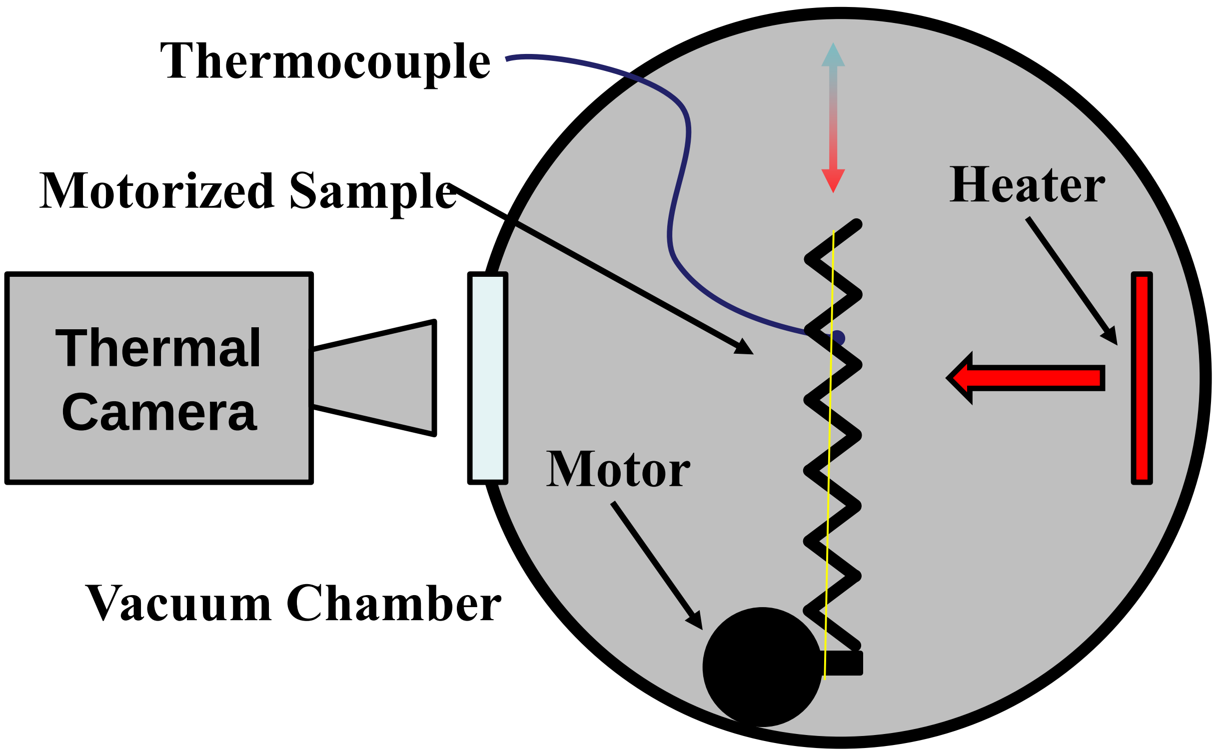
- Flat and folded experimental results both fall within the bounds established by experimental error





Objective 3 – Approach: Environment

- A motorized accordion fold is exposed to varying levels of environmental radiation
- The fold is actuated to the proper cavity angle to maintain steady state conditions



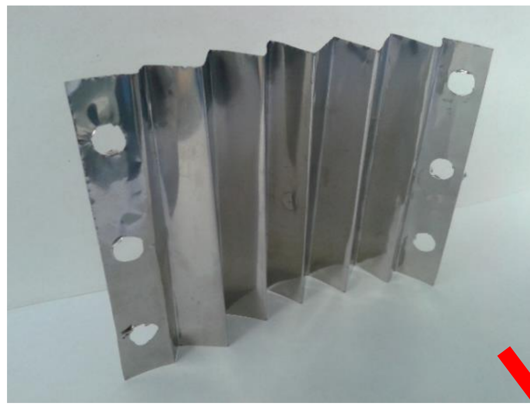
Develop Initial Radiator Prototypes

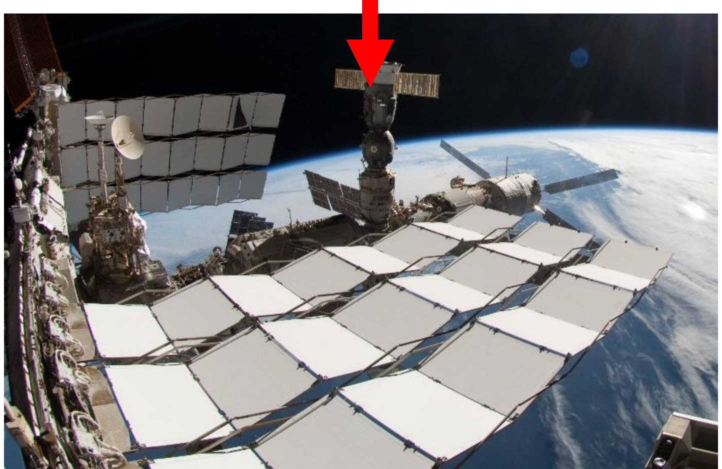
OBJECTIVE 4

1

Objective 4 – Final Design Considerations

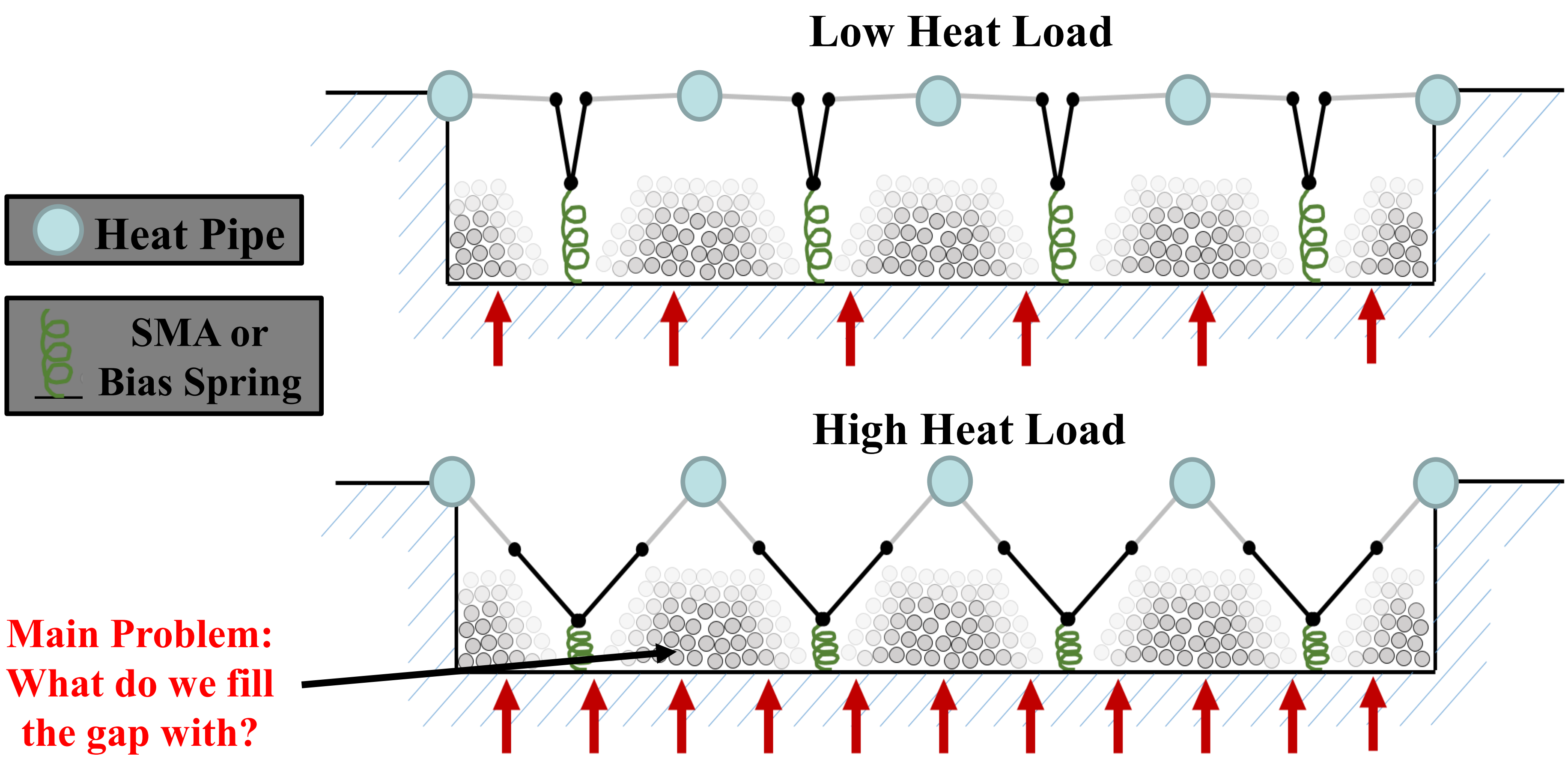
How do you get the waste heat to the radiator?
How will heat conduct along/between panels?
How will the tessellations be actuated?



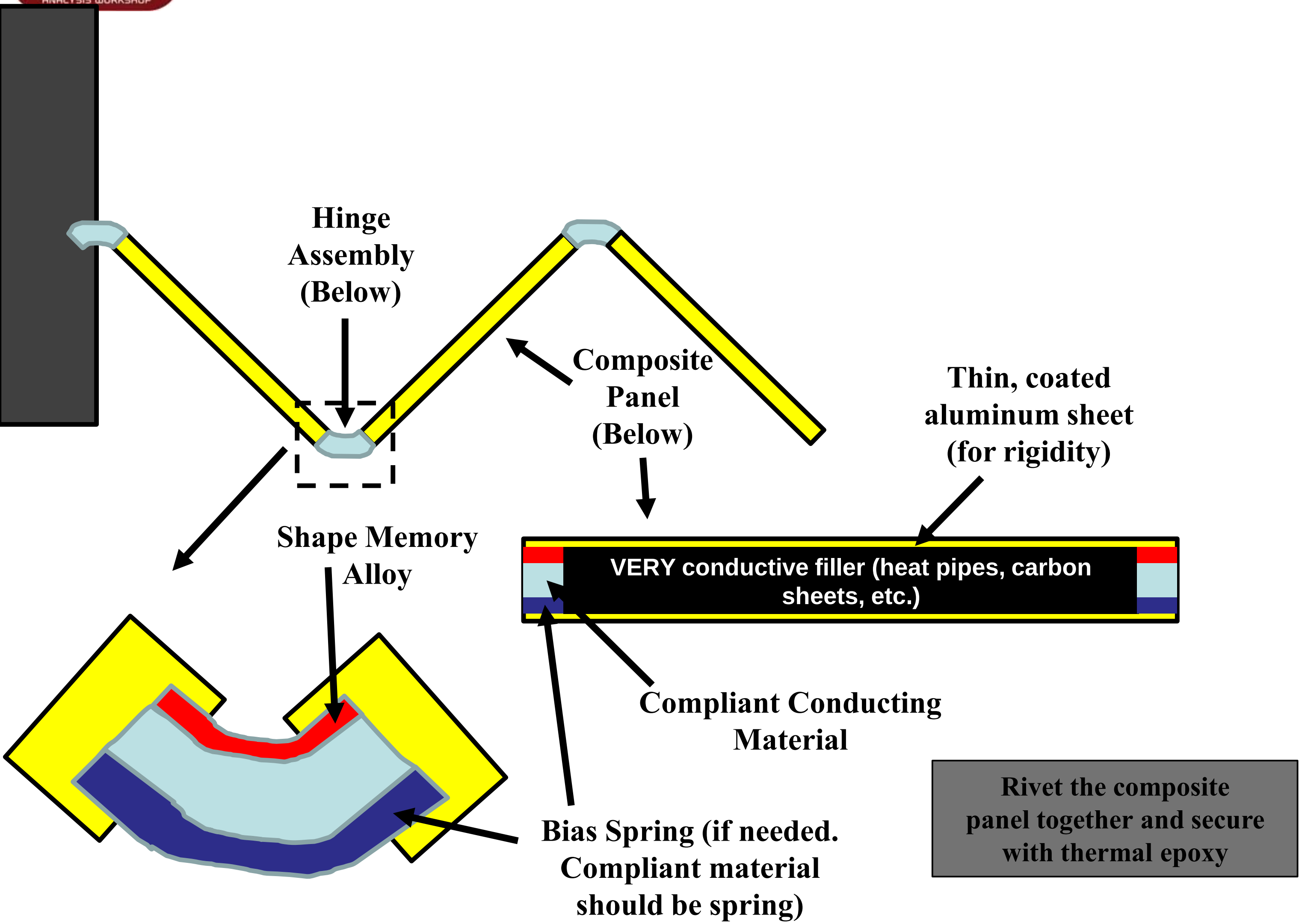


Objective 4 - Radiator Concept #1

- Radiator could be built into an existing panel
- The modified V-groove maintains a constant surface area
- Heat pipes bring the heat load from the spacecraft or heat is present on the back of the panel



Objective 4 - Radiator Concept #2



Benefits:

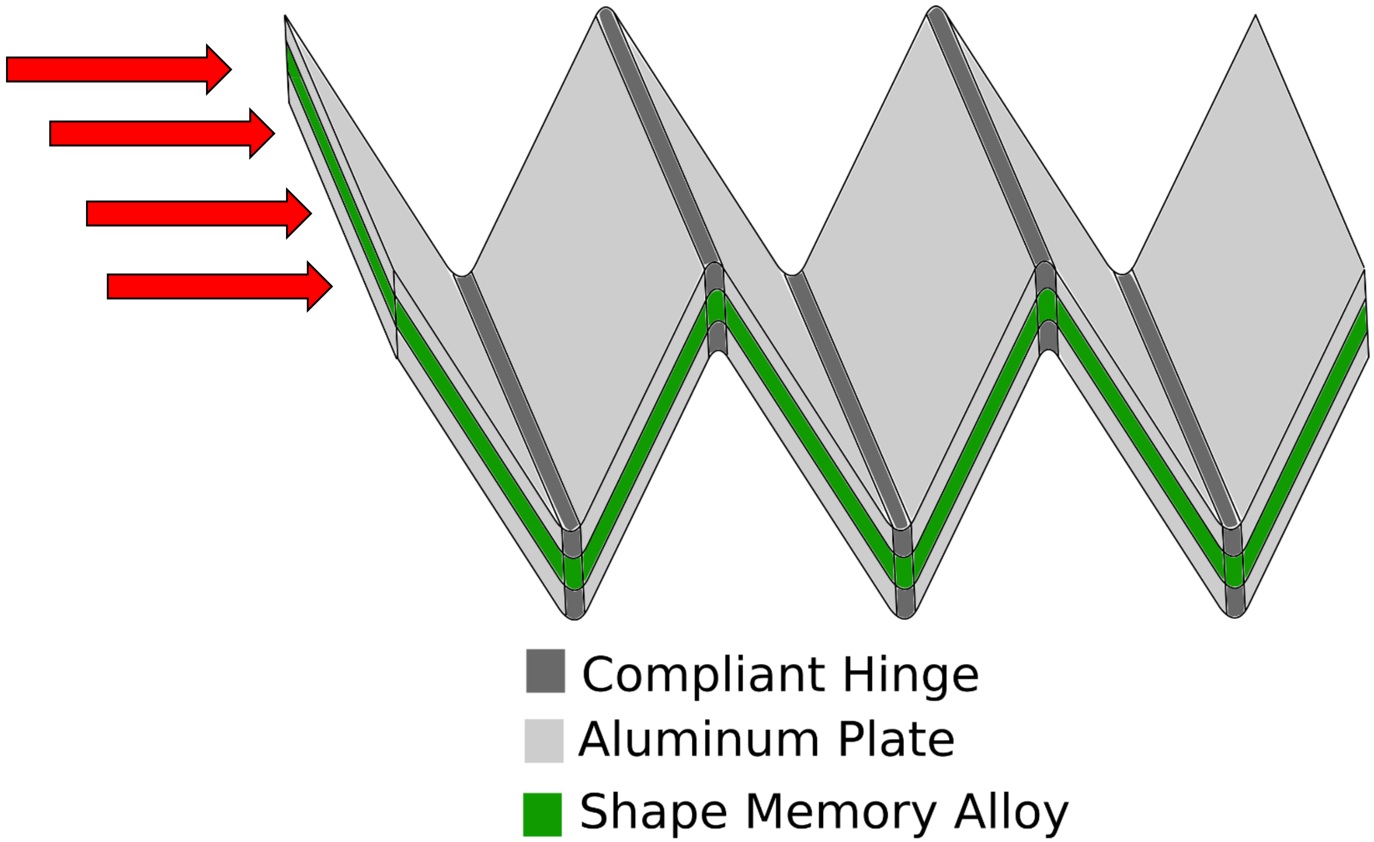
1) Low weight due to the compliant hinge

Challenges:

1) Requires constraint
2) Requires conductive, compliant material

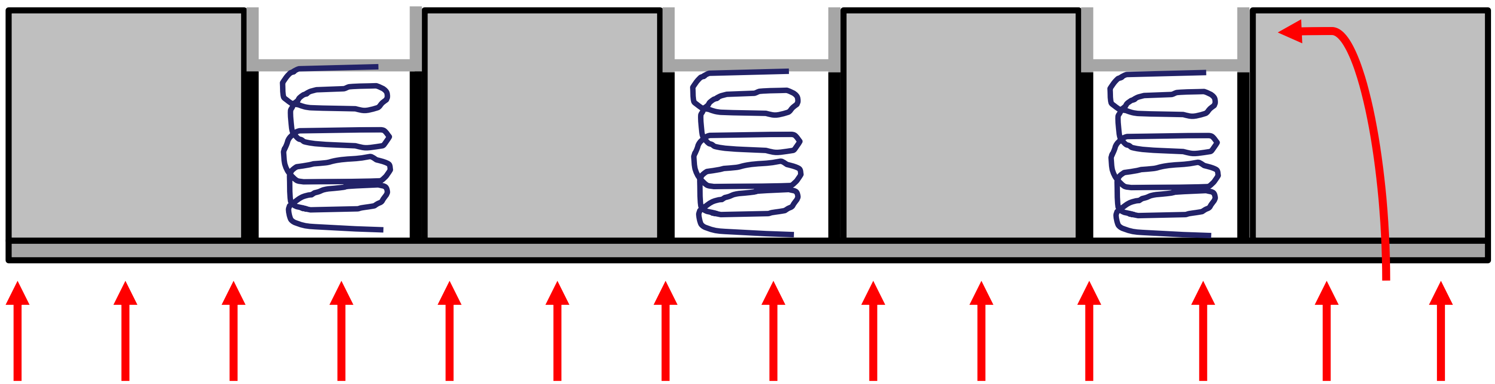
Fin Efficiency

- What is the fin efficiency?
- Consider panel width, length, thickness, etc.

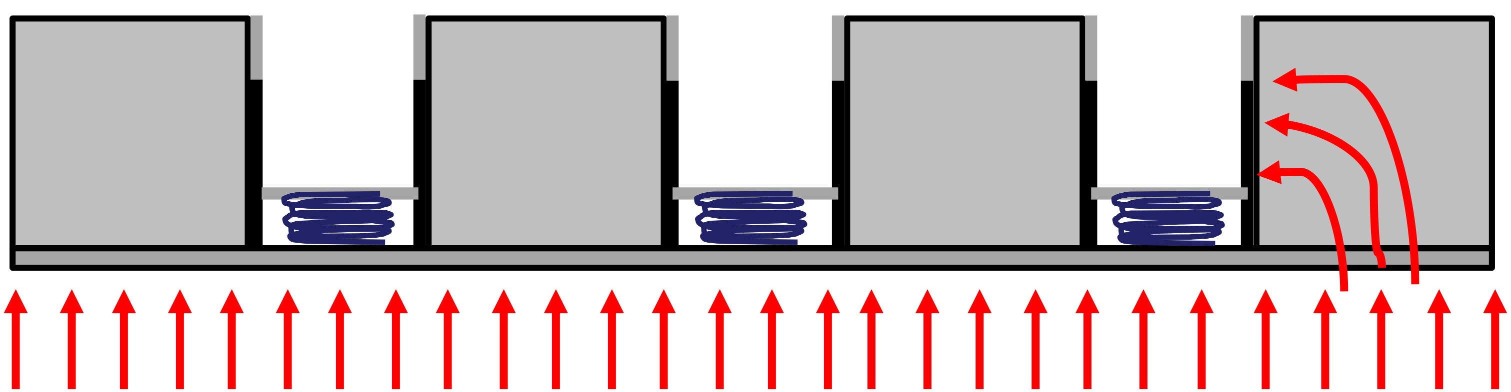


Objective 4 - Radiator Concept #3

Cold Case



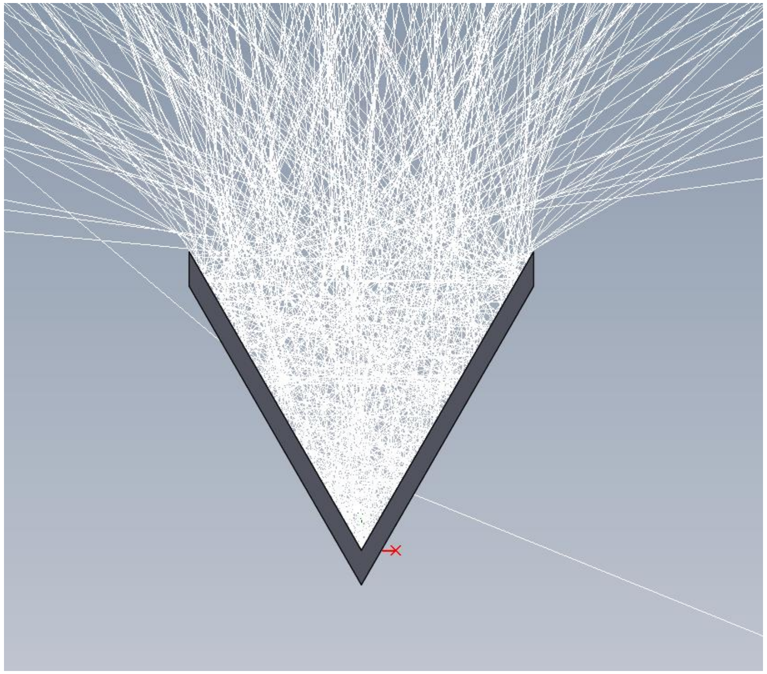
Hot Case



FUTURE WORK

Future Work - Directionality

- Moderately shallow cavities exhibit highly directional behavior, largely ignoring emission and absorption at glancing angles
- This could be utilized to ignore unwanted inputs (solar, albedo, instrument heat loss, etc.)



Acknowledgements

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- Publications

  - Mulford, R. B., Jones, M. R., and Iverson, B. D., 2016, "Dynamic control of radiative surface properties with origami-inspired design," Journal of Heat Transfer, Vol. 138, pp. 032701.
  - Blanc, M. J., Mulford, R. B., Jones, M. R., and Iverson, B. D., 2016, "Infrared visualization of the cavity effect using origami-inspired surfaces," Journal of Heat Transfer, Vol. 138, pp. 020901.
  - Farnsworth, M., Mulford, R. B., Jones, M. R., and Iverson, B. D., 2016, "Variable radiative heat exchange with three-dimensional origami surfaces," ASME International Mechanical Engineering Congress and Exposition, November 11-17, 2016, Phoenix, AZ.
  - Mulford, R. B., Jones, M. R., and Iverson, B. D., 2015, "Dynamic radiative surface properties with origami-inspired topography," NASA Thermal & Fluids Analysis Workshop, August 3-7, 2015, Silver Spring, MD.
  - Mulford, R. B., Jones, M. R., and Iverson, B. D., 2015, "Net radiative heat exchange of an origami-inspired, variable emissivity surface," ASTFE Thermal and Fluids Engineering Summer Conference, August 9-12, 2015, New York, NY.

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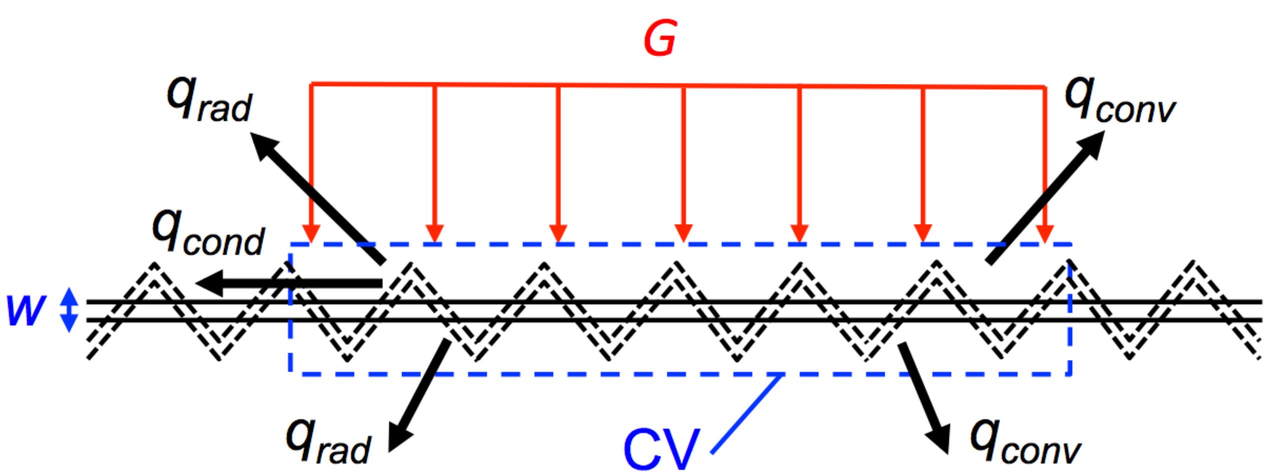
APPENDIX

Objective 1 – Approach

- U(t) characterizes conductive, convective and radiative heat losses

$$U(t) = q_{convection} + q_{conduction} + q_{radiation} = 2h + 2h_r + \frac{Sk}{A_B}$$

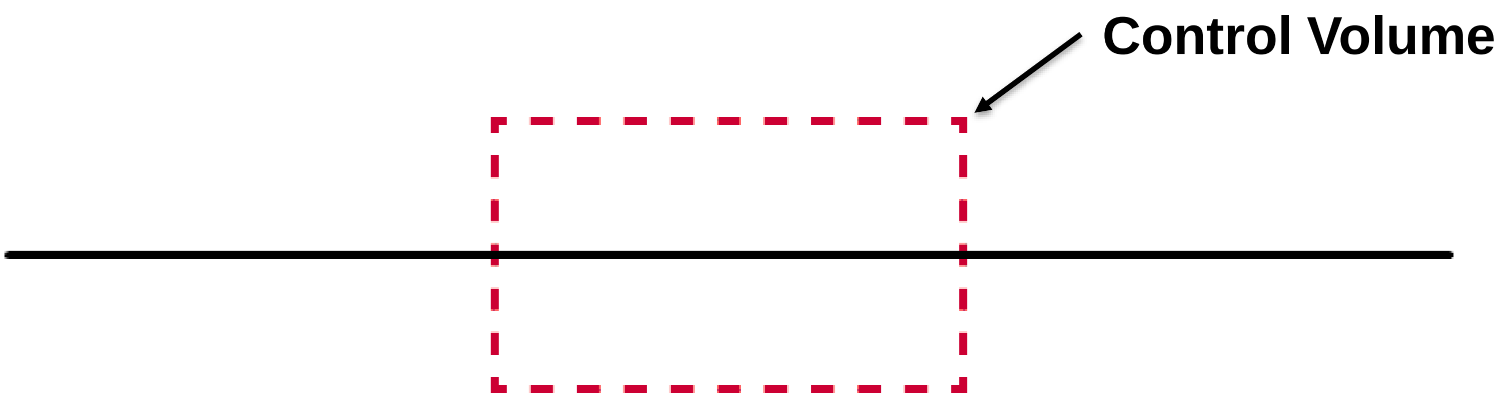
$$\frac{d\theta}{dt} + \sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]\theta = \cancel{\sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P}}$$



Objective 1 – Approach

- Volume ratio accounts for increasing mass in control volume as sample is actuated
- Different origami folds would have different ratios

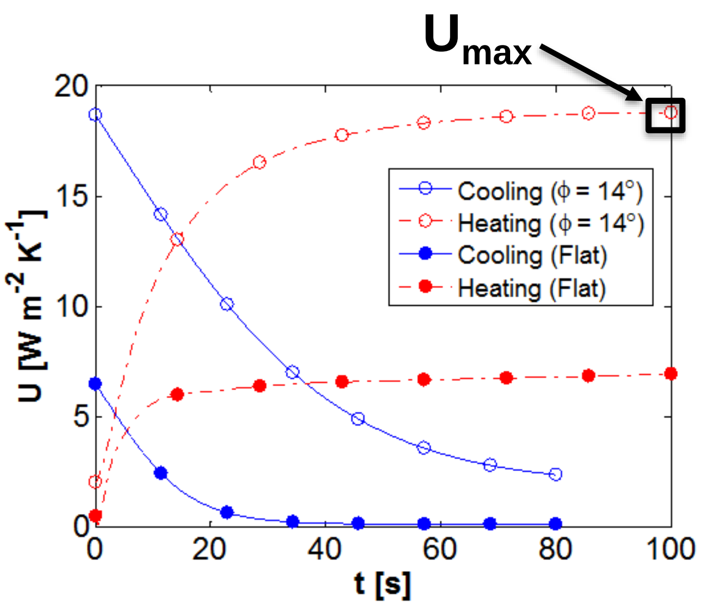
$$\frac{V_B}{V_{folded}} = \frac{A_B}{A_{folded}} = \boxed{\frac{1}{\sin\left(\phi/2\right)}}$$



Objective 1 - Approach

- At steady state, the energy balance gives absorptivity as a function of G, θ_{SS} and U_{max}

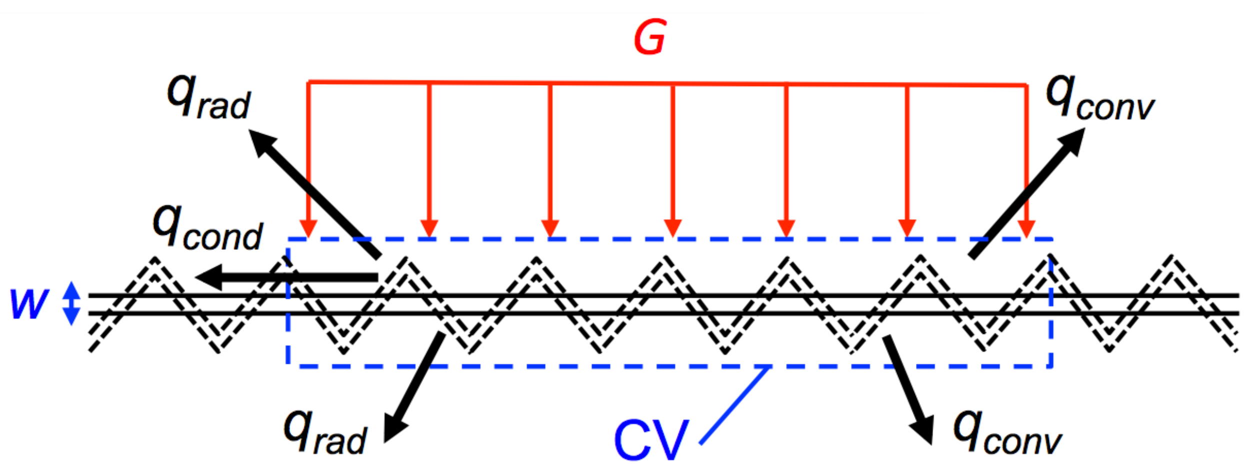
$$\cancel{\frac{d\theta}{dt}}+\sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]\theta=\sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P} \Rightarrow \boxed{\alpha_a=\frac{U_{max}\theta_{SS}}{G_B}}$$



- **All solutions require experimental temperature measurements**

Objective 1 – Definition / Approach

- Validate the use of origami tessellations as variable emissivity surfaces
- Experimentally determine the apparent absorptivity of an accordion fold as a function of angle



$$mC_P \frac{dT}{dt} = \alpha_a G_B A_B - (q_{conv} + q_{rad} + q_{cond})_{losses}$$

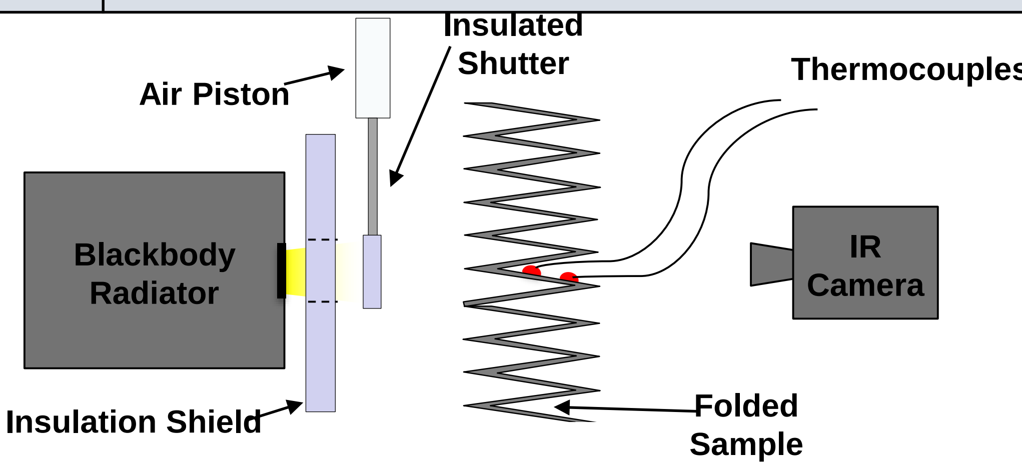
$$\frac{d\theta}{dt} + \underbrace{\sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]}_{\text{Heat Loss Term}}\theta = \underbrace{\sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P}}_{\text{Heat Addition Term}}$$

Objective 1 - Approach

$$\frac{d\theta}{dt}+\sin\left(\frac{\phi}{2}\right)\left[\frac{U(t)}{\rho w C_P}\right]\theta=\sin\left(\frac{\phi}{2}\right)\frac{\alpha_a G_B}{\rho w C_P}$$

Integrating Factor Method	Direct Method
$\alpha_a=\dfrac{\dfrac{U_{\max}}{G_B}(\theta-\theta_0)}{1-e^{\frac{-U_{\max}t}{\rho w C_P}\sin\left(\frac{\phi}{2}\right)}}$	$\alpha_a=\dfrac{\rho w C_P}{G_B\sin\left(\frac{\phi}{2}\right)}\left[\dfrac{d\theta}{dt}+\sin\left(\dfrac{\phi}{2}\right)\dfrac{U(\Delta T(t))}{\rho w C_P}\theta\right]$

$$\alpha_a=\frac{U_{\max}\theta_{SS}}{G_B}$$



Objective 1 – Results

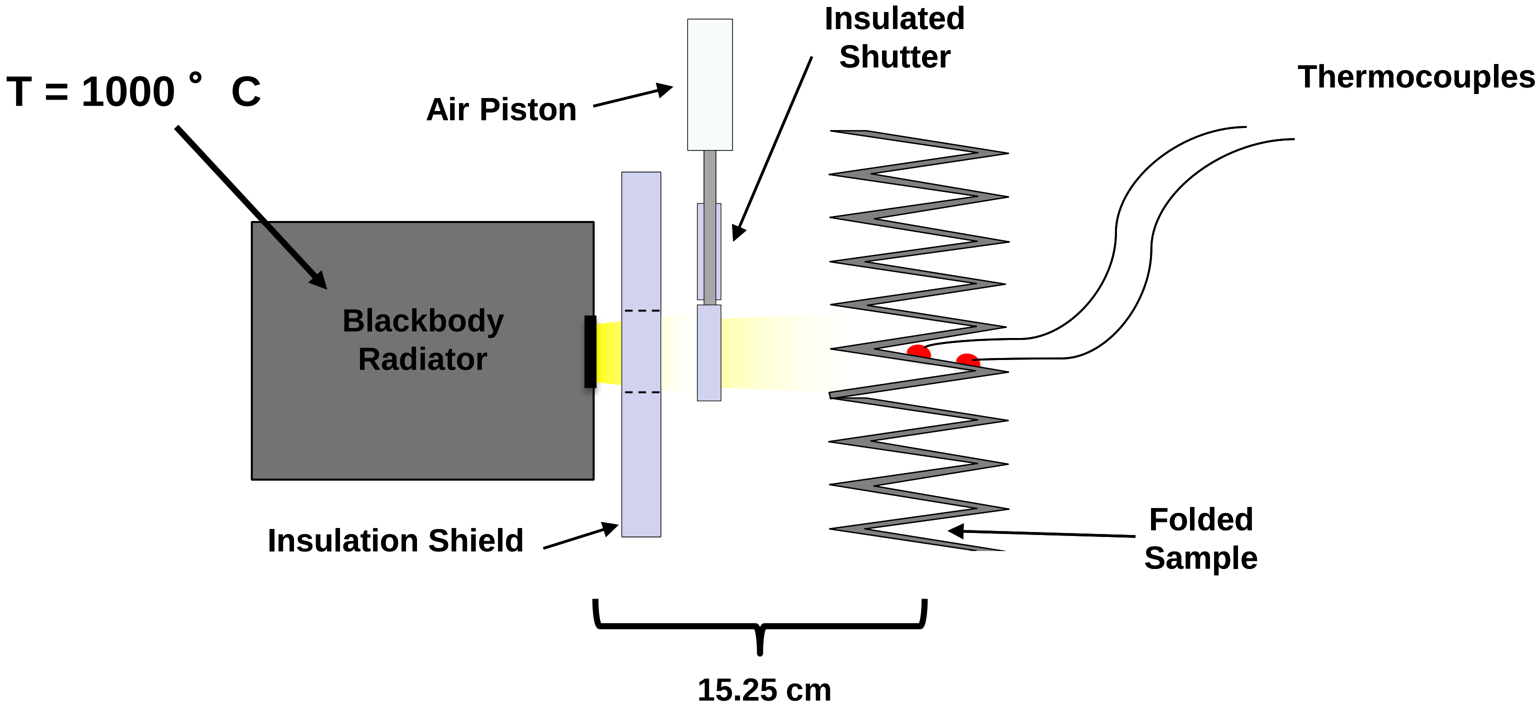
- Flat sample was measured with a reflectometer
- Independent verification of inverse model results

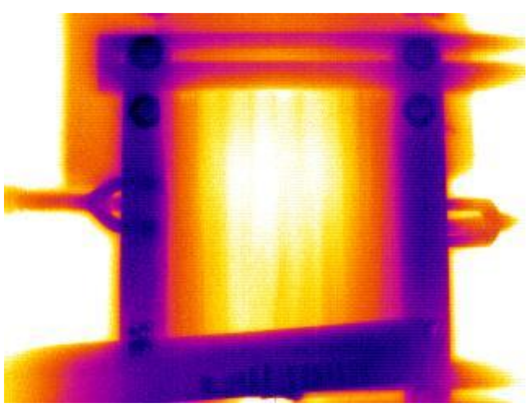
Test #	Spectral Range (Micrometers)					
	1.5 – 2.0	2.0 – 3.5	3.0 – 4.0	4.0 – 5.0	5.0 – 10.5	10.5 – 21.0
	Spectral Reflectivity					
1	0.965	0.969	0.966	0.977	0.982	1.005
2	0.967	0.972	0.971	0.973	0.983	1.01
3	0.965	0.969	0.973	0.977	0.98	0.986

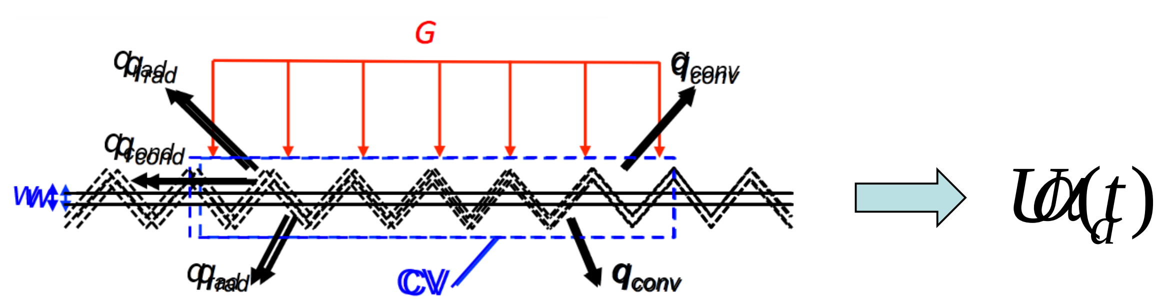
Emissometer Absorptivity	**0.028**
Steady State Model Absorptivity	**0.028**

$$\alpha = \sum_{i=1}^{6} F_i \left(1 - \rho_{r,i}\right)$$

Objective 1 – Approach

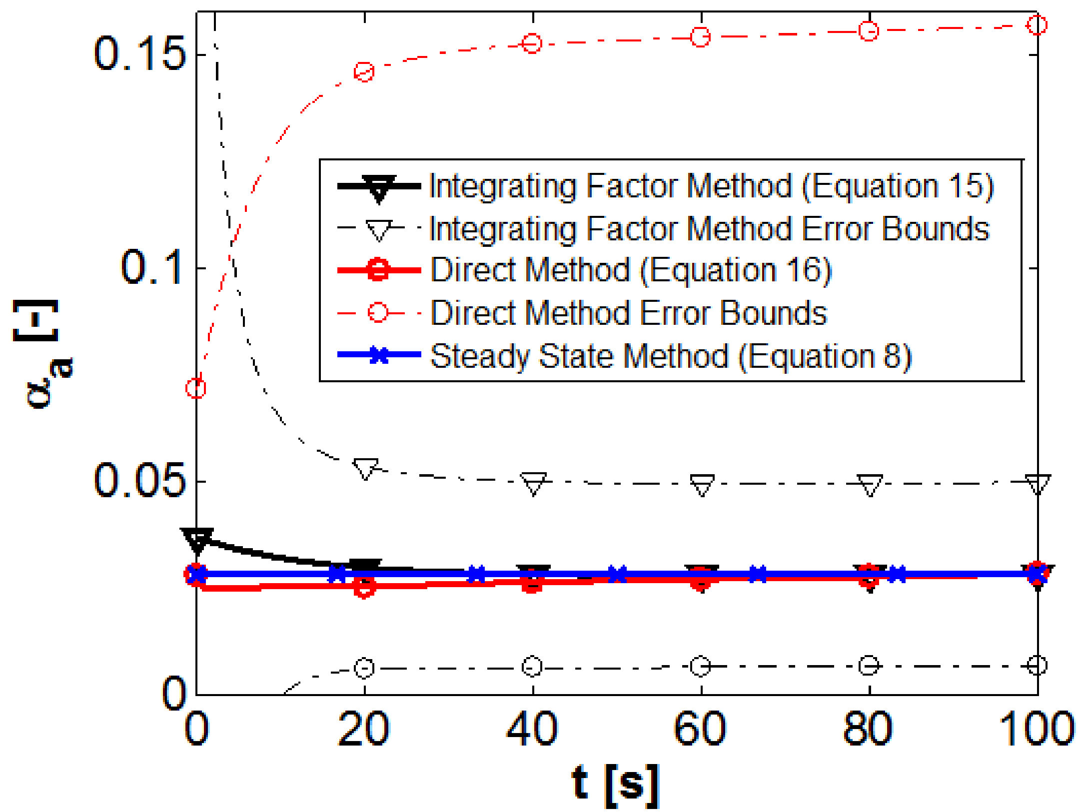




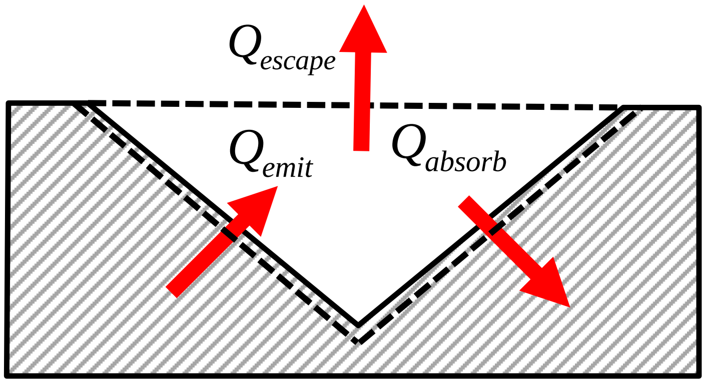


Objective 1 – Results

- Apparent absorptivity results with respect to time for the three methods
- All solutions converge to one value



Ray Tracing – Emissivity Thermal Model



$$Q_{emit} = Q_{absorb} + Q_{escape}$$

$$Q_{emit} = \varepsilon \sigma A_{emit} T^4 \qquad Q_{escape} = \varepsilon_a \sigma A_{opening} T^4$$

$$\varepsilon \sigma A_{emit} T^4 = \varepsilon_a \sigma A_{opening} T^4 + Q_{absorb}$$

Rearrange to give apparent emissivity

$$\varepsilon_a = \varepsilon \frac{A_{emit}}{A_{opening}} - \frac{Q_{absorb}}{\sigma T^4 A_{opening}}$$

From the definition of Q_{emit}

$$\sigma T^4 = \frac{Q_{emit}}{\varepsilon A_{emit}}$$

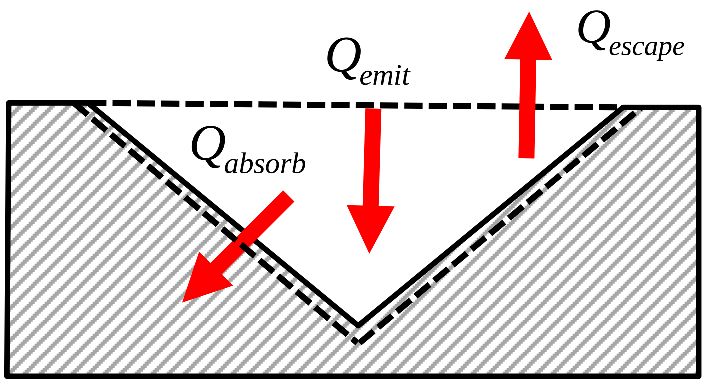
Plug into apparent emissivity equation

$$\varepsilon_a = \varepsilon \frac{A_{emit}}{A_{opening}} \left[1 - \frac{Q_{absorb}}{Q_{emit}} \right]$$

Using the original energy balance and equating thermal model to ray tracing results gives:

$$\boxed{\varepsilon_a = \varepsilon \frac{A_{emit}}{A_{opening}} \frac{Q_{escape}}{Q_{emit}} = \varepsilon \frac{A_{emit}}{A_{opening}} \frac{N_{escape}}{N_{emit}}}$$

Ray Tracing – Absorptivity Thermal Model



$$Q_{emit} = Q_{absorb} + Q_{escape}$$

From definition of apparent reflectivity

$$Q_{escape} = \rho_a Q_{emit}$$

$$Q_{emit} - \rho_a Q_{emit} = Q_{absorb}$$

Assuming opaque

$$1 - \rho_a = \alpha_a$$

Final Expression

$$\alpha_a = \frac{Q_{absorb}}{Q_{emit}} = \frac{N_{absorb}}{N_{emit}}$$

From Ohwada[1] we learn that apparent absorptivity and apparent emissivity are equivalent for an isothermal cavity

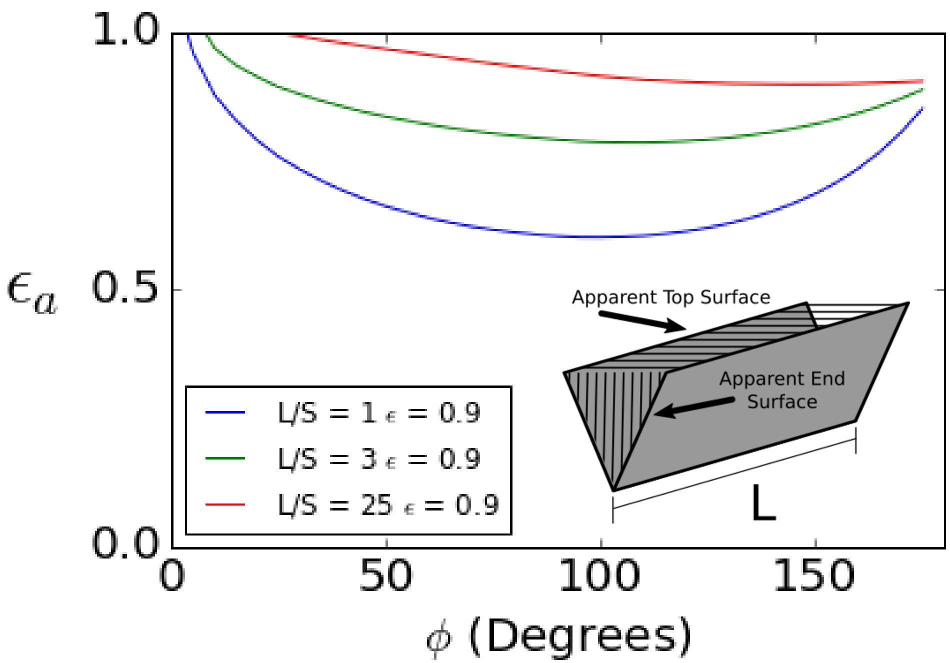
$$\boxed{\alpha_a = \frac{N_{absorb}}{N_{emit}} = \varepsilon_a}$$

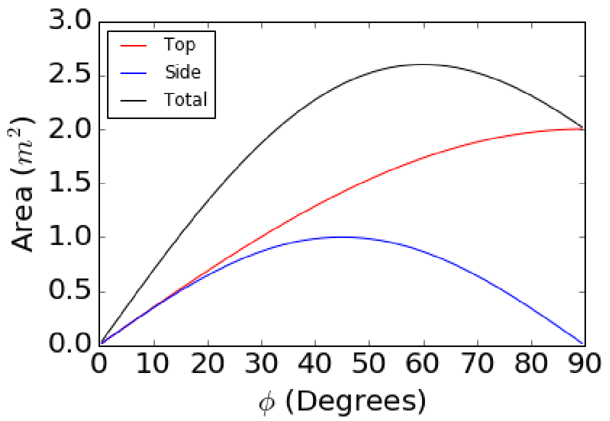
[1] - Ohwada, Y. 1988 "Mathematical proof of an extended Kirchoff Law for a cavity having direction-dependent characteristics" Journal of the Optical Society of America 5(1). 141-145.

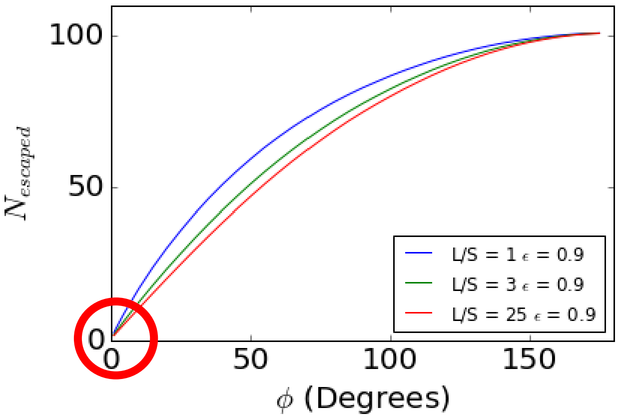
Results – Accordion:

- Apparent emissivities below the intrinsic surface value are a result of the area of the sides
- Values above unity are not possible and are due to large error experienced at very small angles and high emissivities

$$\varepsilon_a = \varepsilon \frac{A_{emit}}{A_{opening}} \frac{N_{escape}}{N_{emit}}$$







Results - Accordion

- All cases showed a convergence of 0.2% or less. The extreme cases are shown here (L/S = 1 or 5 and emissivity = 0.028 or 0.9)